CONFIDENTIAL

SUMMARY TECHNICAL REPORT
OF THE
NATIONAL DEFENSE RESEARCH COMMITTEE

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SUMMARY TECHNICAL REPORT OF DIVISION 17, NDRC

VOLUME 4

COMBAT TRAINING EQUIPMENT AND TESTING DEVICES

OFFICE OF SCIENTIFIC RESEARCH AND DEVELOPMENT

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NATIONAL DEFENSE RESEARCH COMMITTEE

JAMES B. CONANT, CHAIRMAN

DIVISION 17

GEORGE R. HARRISON, CHIEF

WASHINGTON, D. C., 1946

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NOTES ON THE ORGANIZATION OF NDRC

The duties of the National Defense Research Committee were (1) to recommend to the Director of OSRD suitable projects and research programs on the instrumentalities of warfare, together with contract facilities for carrying out these projects and programs, and (2) to administer the technical and scientific work of the contracts. More specifically, NDRC functioned by initiating research projects on requests from the Army or the Navy, or on requests from an allied government transmitted through the Liaison Office of OSRD, or on its own considered initiative as a result of the experience of its members. Proposals prepared by the Division, Panel, or Committee for research contracts for performance of the work involved in such projects were first reviewed by NDRC, and if approved, recommended to the Director of OSRD. Upon approval of a proposal by the Director, a contract permitting maximum flexibility of scientific effort was arranged. The business aspects of the contract, including such matters as materials, clearances, vouchers, patents, priorities, legal matters, and administration of patent matters were handled by the Executive Secretary of OSRD.

Originally NDRC administered its work through five divisions, each headed by one of the NDRC members. These were:

Division A—Armor and Ordnance
Division B—Bombs, Fuels, Gases, & Chemical Problems
Division C—Communication and Transportation
Division D—Detection, Controls, and Instruments
Division E—Patents and Inventions

In a reorganization in the fall of 1942, twenty-three administrative divisions, panels, or committees were created, each with a chief selected on the basis of his outstanding work in the particular field. The NDRC members then became a reviewing and advisory group to the Director of OSRD. The final organization was as follows:

Division 1—Ballistic Research
Division 2—Effects of Impact and Explosion
Division 3—Rocket Ordnance
Division 4—Ordnance Accessories
Division 5—New Missiles
Division 6—Sub-Surface Warfare
Division 7—Fire Control
Division 8—Explosives
Division 9—Chemistry
Division 10—Absorbents and Aerosols
Division 11—Chemical Engineering
Division 12—Transportation
Division 13—Electrical Communication
Division 14—Radar
Division 15—Radio Coordination
Division 16—Optics and Camouflage
Division 17—Physics
Division 18—War Metallurgy
Division 19—Miscellaneous
Applied Mathematics Panel
Applied Psychology Panel
Committee on Propagation
Tropical Deterioration Administrative Committee

NDRC FOREWORD

As events of the years preceding 1940 revealed more and more clearly the seriousness of the world situation, many scientists in this country came to realize the need of organizing scientific research for service in a national emergency. Recommendations which they made to the White House were given careful and sympathetic attention, and as a result the National Defense Research Committee [NDRC] was formed by Executive Order of the President in the summer of 1940. The members of NDRC, appointed by the President, were instructed to supplement the work of the Army and the Navy in the development of the instrumentalities of war. A year later, upon the establishment of the Office of Scientific Research and Development [OSRD], NDRC became one of its units.

The Summary Technical Report of NDRC is a conscientious effort on the part of NDRC to summarize and evaluate its work and to present it in a useful and permanent form. It comprises some seventy volumes broken into groups corresponding to the NDRC Divisions, Panels, and Committees.

The Summary Technical Report of each Division, Panel, or Committee is an integral survey of the work of that group. The first volume of each group's report contains a summary of the report, stating the problems presented and the philosophy of attacking them, and summarizing the results of the research, development, and training activities undertaken. Some volumes may be "state of the art" treatises covering subjects to which various research groups have contributed information. Others may contain descriptions of devices developed in the laboratories. A master index of all these divisional, panel, and committee reports which together constitute the Summary Technical Report of NDRC is contained in a separate volume, which also includes the index of a microfilm record of pertinent technical laboratory reports and reference material.

Some of the NDRC-sponsored researches which had been declassified by the end of 1945 were of sufficient popular interest that it was found desirable to report them in the form of monographs, such as the series on radar by Division 14 and the monograph on sampling inspection by the Applied Mathematics Panel. Since the material treated in them is not duplicated in the Summary Technical Report of NDRC, the monographs are an important part of the story of these aspects of NDRC research.

In contrast to the information on radar, which is of widespread interest and much of which is released to the public, the research on subsurface warfare is largely classified and is of general interest to a more restricted group. As a consequence, the report of Division 6 is found almost entirely in its Summary Technical Report, which runs to over twenty volumes. The extent of the work of a Division cannot therefore be judged solely by the number of volumes devoted to it in the Summary Technical Report of NDRC; account must be taken of the monographs and available reports published elsewhere.

The research work of Division 17 included a wide variety of projects, ranging from the detection of land mines to the characteristics of the human ear, from helium purity indicators to the telemetering of strain gauges, from odographs to sound-ranging devices. It is a tribute to the broad knowledge of the Division Chiefs—Paul Klopsteg and, later, George R. Harrison—and to the versatility of the men who worked under them that so diverse a program was handled so competently.

A considerable portion of the work of Division 17 had to do with the shattering noise of modern war, and answers were sought and supplied to such questions as: How much noise can a human being stand? What clues must the human ear have in order to understand a spoken message? How much distortion can be tolerated? These and other phases of the Division's work are dealt with in the Summary Technical Report prepared under the direction of the Division Chief and authorized by him for publication.

The diversity of the Division's projects made it inevitable that its staff should be composed of men with many types of scientific training and that the Division should draw on contractors with a wide range of experience and skills. The studies of noise, in particular, meant that the technical staff must include physicists, acousticians, and psychologists. For the ability and devotion of these men of many aptitudes we express our gratitude.

Vannevar Bush, Director
Office of Scientific Research and Development

J. B. Conant, Chairman
National Defense Research Committee

FOREWORD

THE APPLIED PHYSICS DIVISION of the Office of Scientific Research and Development [OSRD] was organized late in 1942 under the chairmanship of Dr. Paul E. Klopsteg, who was responsible for the work of the Division until shortly before the completion of its work when other duties required his full attention. Most of the projects which had been initiated by the Instruments Section of the National Defense Research Committee [NDRC] during 1940 and 1941 and which were not concerned with optics were turned over to the Applied Physics Division on its inauguration. Dr. Klopsteg as Chief and Dr. E. A. Eckhardt as Deputy Chief went with them from the Instruments Section to the new Division.

The Summary Technical Report which is presented in these volumes thus covers the accomplishments of projects set up by both Section D-3 and Division 17. The work of the Division covered a very wide range of fields. The term "applied physics" served in lieu of a more descriptive name for a Division which was in fact the one to which was assigned any scientific problem which did not properly come under one of the other divisions of NDRC.

Actually the Division was an association of three Sections having rather dissimilar responsibilities and fields of activity. In setting up these Sections it was necessary to group the projects already under way into a small number of coherent categories, and those chosen were Sound, Electricity, and General Instrumentation. The work of the Division consisted entirely of the integrated efforts of these three Sections, whose membership will be found listed on a succeeding page.

For more detailed reports on the technical work of the Division than are contained herewith the detailed contractors' reports of Division 17 should be consulted, and appropriate reference to these have been made throughout the present volumes. The results obtained are also presented in less technical form in that volume of the history of OSRD entitled *Optics and Applied Physics in World War II.*

GEORGE R. HARRISON
Chief, Division 17

PREFACE

THE RESEARCH AND DEVELOPMENT PROGRAM of Division 17 of the National Defense Research Committee [NDRC] was concerned with those problems in physics not specifically covered in other Divisions of NDRC. As the result, the Division fell heir to a myriad of miscellaneous problems of a physical nature which, themselves, were not often interrelated. It would have been exceedingly difficult, if not impossible, for Division 17 to set up within itself a sufficient number of Sections to deal specifically with all the various classes of problems which fell under its jurisdiction. Therefore, the projects of the Division were assigned to one of three Sections —Section 17.1, Instruments; Section 17.2, Electrical Equipment; and Section 17.3, Acoustics—whose broad titles permitted a general, even if somewhat loose, classification. It was not always easy to decide, at times, under which of these three broad categories a given project should be placed. In these cases, considerations such as immediate convenience and availability of experienced personnel were often the determining factors.

The Summary Technical Report describing the activities of Division 17 is presented in four volumes. In an attempt to achieve a little greater uniformity of subject matter, the projects were organized within the various volumes without regard to their Section classification. Consequently, there is, on the whole, little relationship between volume and Section number. Because of the varied problems dealt with in the Division's program, very little continuity is to be found from chapter to chapter in any volume. Each chapter attempts to summarize independently the results of a particular project.

Since there were a large number of diversified projects in Division 17, it was obviously impossible to do justice to each, even in summary. It is not intended that the importance of any project described herein should be judged by the amount of page space allotted to it. Naturally, certain problems involved more research and development than others before they could be brought to a successful conclusion. In many cases, this is reflected in the Summary Technical Report. On the other hand, the presentation of the projects may mirror the enthusiasm (or lack of it) of the individual author at the time of writing. Therefore, the reader who desires more than a broad panorama of the Division's activities is referred to the Microfilm Index for more complete details.

This is the fourth and final volume of the Summary Technical Report of Division 17. The devices and techniques discussed herein are for home-front instrumentation rather than for battle-front instrumentation. That is, this volume deals with devices and techniques which would affect the battle front indirectly, through facilitating production and/or perfection of matériel or through improving the training and preparations of personnel for battle.

Each chapter in this volume discusses either a single Division 17 project or a related group of projects. As shown by the by-lines in the Contents and in the chapter headings, a number of authors have assisted in preparing this book. This opportunity is taken to express sincere appreciation for such assistance. It should be borne in mind that although every reasonable effort has been made to keep this book free from error, the authors have ordinarily not been setting forth their own personal experiences or results of personal research. The chapters are derived from careful and conscientious study of contractors' reports and associated publications. Neither the authors nor the Office of Scientific Research and Development [OSRD] are accountable for the correctness of the facts which form the basis for this volume.

This opportunity is taken to express appreciation for other assistance in connection with this volume: the research done for the OSRD under contract and reported herein; the time and effort expended by personnel of Division 17 and its Sections in reading and criticizing manuscripts; and the care exercised by the Summary Reports Group in publishing the material.

F. L. YOST
Editor

CONTENTS

Chapter 1

TELEMETERING OF STRAIN GAUGES AND INSTRUMENTS [a]

By *George E. Beggs, Jr.*[b]

1.1 ABSTRACT

THIS REPORT DESCRIBES the results of various projects conducted under the supervision of the National Defense Research Committee in the field of telemetering of strain gauges and other instruments from aircraft to ground by a radio link, to allow remote-control testing of high-speed aircraft. There is included a rather general discussion of various systems of multiplexing to permit the handling of numerous channels of information by the radio link. This report presents a general survey of the telemetering field as of September 1945, including developments made by groups under Service or NDRC supervision.

A brief description of the application of certain telemetering principles to transmission of data from guided missiles is also included.

1.2 INTRODUCTION

Development of small, high-speed aircraft, approaching sonic speeds under certain conditions, has made flight testing of experimental and production prototypes increasingly difficult by methods in vogue at the beginning of the war. The phenomena of compressibility, flutter, and other instabilities evident at high speed demanded very accurate means for measurement and analysis of dynamic data concerned with stresses and accelerations within the aircraft. Furthermore, to allow reasonably complete analysis of the structure, many items of information were desired simultaneously. Such observation and recording could not be done by a test pilot, even if he were riding only as a passenger, without part of his attention necessarily being devoted to the flying.

Originally, methods were employed in which data of the type noted above were recorded on multi-channel oscillographs mounted in the aircraft, the pilot being present only to put the plane through appropriate maneuvers. Numerous test flights of this type were made, and valuable data were obtained. However, testing under conditions of greatest severity was seldom possible, due to the human element. In addition, structural failures causing loss of the aircraft often resulted in loss of the records.

It became apparent that complete tests could be obtained only by remote radio control of a pilotless aircraft, the data being transmitted by radio to a ground recording station. Television apparatus was used in some cases, but a need for intelligence data to be transmitted at higher frequency emphasized the necessity for equipment specifically developed to transmit strain-gauge, accelerometer, and pressure data. The process of transmitting multi-channel data is known as telemetering and, in the case of aircraft telemetering, involves the use of a means of multiplexing numerous intelligence channels on a single radio link. Multiple radio links are undesirable, since little space is available for multiple-antenna installations and duplication of numerous radio circuits is uneconomical with respect to materials, space, and power.

In addition to the requirements for telemetering apparatus for aircraft, there arose later in the program a need for similar, more compact apparatus for the development and testing of guided missiles. In this case the need was even more urgent, since no data could be obtained by the use of a pilot even in early test stages. The basic principles of aircraft telemetering proved applicable to the development of this more specialized equipment.

1.3 MILITARY REQUIREMENTS

Basically, military requirements for telemetering are constantly in a state of flux, since available test data from any given system invariably indicate the need for more channels,

[a] AC-40, NA-133, NA-134, NA-152, NA-242.
[b] Technical Aide, Section 17.1-17.2, NDRC.

greater accuracy, higher frequency response, less weight, size, power consumption, and other improvements.

The latest phase of telemetering completed by NDRC demanded the following characteristics:

1. A minimum of 14 channels of information.
2. Each channel to respond to intelligence variations of 0 to 200 c.
3. Intermodulation and random inaccuracies to be as low as possible, preferably less than 2 per cent.
4. Transmission by a single radio link.
5. Ground recording by a standard multichannel recording oscillograph.
6. Adaptability to signals from wire strain gauges, accelerometers, and other similar devices.
7. Small, lightweight, reliable, low power-consumption airborne apparatus operable from 24- to 30-v d-c supply.
8. Range of 30 miles or more, regardless of aircraft attitude.

Various groups attempted several approaches to the problem, one of which led to a successful solution.

1.4 SUMMARY

Early work in the field of telemetering was initiated because of Army requests for apparatus which would transmit data from instruments in guided missiles (i.e., pilotless aircraft or controlled bombs) to a control location, so that the operator could maneuver and guide the missile in offensive operations. As the development progressed along various lines of instrument telemetering, new interest arose in the possibility of applying the transmission of data in this manner to the study of new types of aircraft under test, thus somewhat changing the emphasis of the program.

Early in 1943, testing of high-speed aircraft introduced the necessity for transmission of data derived from resistance strain gauges and instruments of a similar nature, with a relatively high degree of accuracy and over a large number of channels. The final equipment developed has proved sufficiently versatile to transmit readings derived from standard, or from somewhat modified aircraft instruments and from strain gauges, allowing application of the apparatus to numerous and diverse problems of testing and operation.

In the field of instrument telemetering, three contracts were initiated under NDRC. The contract with the National Broadcasting Company [NBC][1-3] involved the development of a relatively narrow-band television system of low definition for reproducing instrument readings. These readings made by the television camera in the aircraft were to register at a ground location with sufficient clarity to obtain data with the desired degree of accuracy. This system was intended to replace the Block I[c] television set which was comparatively bulky and required considerable band width in the radio-frequency spectrum, although it gave good quality reception. The NBC program utilized the new 2-in. Orthicon camera tube as a basis for a new low-quality system of 10 frames per second, 200 lines. The development of this system was completed early in 1943 and flight tests of the apparatus were made with the assistance of the Aircraft Radio Laboratory at Wright Field. Although the flight tests proved satisfactory, it was found that new developments in the field of high-definition television, specifically Block III[c] equipment, superseded the low-definition type. Since band-width requirements no longer appeared to be critical and the bulk and weight of the Block III system were comparable to the NBC-NDRC developments, this system was chosen. Furthermore, emphasis at this time shifted to the transmission of strain-gauge data which could be handled in some degree more satisfactorily by other means.

The Hazeltine Electronics Corporation[4-10] made an approach to the instrument-telemetering problem by utilizing a system of line scanning essentially in one dimension, rather than the two-dimensional used in television. This allowed reduction of the required band width by transmitting only pertinent data on the position of instrument pointers and the scale zeros, without transmitting unnecessary data on the general appearance of the panel. The zero and a moving pointer on each instrument were equipped

[c] Army-Navy identification of airborne television apparatus developed by RCA, Camden, N. J.

with magnetic strips. The pointer position was determined by scanning the instrument dial with a pickup coil of high permeability, mechanically driven in a circle concentric with the dial. The pulses produced in the pickup by the zero and pointer magnets were transmitted in time sequence over a standard communication link and separated at the receiving end. Following separation, the items were applied to electronically scanned cathode-ray tubes. The pulses indicating pointer position were used to intensify the scanning trace at the appropriate times so that the face of the cathode-ray tube presented two dots angularly separated by the same amount as the original zero and pointer. This is essentially a mechanical commutation system. It was flight-tested at Wright Field and performed satisfactorily but its usefulness was limited by its inability to transmit rapid variations in instrument readings, and by its size and mechanical complexity at the transmitting end. Thus, with a shift in interest from telemetering aircraft instruments to telemetering strain-gauge indications and with the development of the Block III television apparatus under Service supervision, no applications of this development ensued.

The Rudolph Wurlitzer Company,[11,12] under NDRC contract, approached the problem of instrument telemetering by the method of subcarrier pulse modulation, the subcarriers being combined and transmitted over a single radio link to be separated at the receiving end by band-pass filters. The pulse length transmitted for any instrument represented the indication of the instrument in a linear relation. This system was basically sound and proved itself relatively satisfactory in flight tests, but the adaptation of standard instruments to produce variable pulse lengths required complex electromechanical transducers adapted from Magnesyn-Autosyn systems developed by Bendix. (See Figures 16, 17, 18, 19, and 20.) Furthermore, the pulsing rate of the system was too low to allow transmission of other than slow variations of the instruments. The change in emphasis to the strain-gauge program required the adaptation of this system to strain-gauge transmission which was quite difficult.

With the advent of an intensive development of high-speed fighter aircraft there was increasing need for a great number of channels to be transmitted from strain gauges of the wire-resistance type to observe flutter and various peak-load conditions. The background knowledge gained from the instrument-telemetering program showed that there were difficulties encountered from intermodulation between some channels, that the intelligence response was not of sufficiently high frequency, and that the number of channels available (with the exception of television, five at most) was inadequate. It appeared desirable therefore to make a general survey of methods for telemetering strain-gauge information, as well as instrument indications, and to set up a comprehensive program to study these basic problems and to develop apparatus capable of satisfying the aircraft test program.

Accordingly, in April 1943, two sets of specifications were drawn up covering approaches to the strain-gauge telemetering development by subcarrier transmission of intelligence and by time-division multiplexing (i.e., commutation). In both cases the initial requirements were substantially the same: the intelligence frequency to be transmitted should be of the order of 100 c to 200 c, and a minimum of 14 (preferably 20) channels of information should be available for transmission over a single radio link with accuracies within 2 to 5 per cent on any channel. In addition, it was requested that the basic differences between the two types of multiplexing be studied to see under what conditions a particular system might have advantages.

Three new NDRC contract arrangements were established to study development of subcarrier and time-division multiplexed telemetering: one with the Wurlitzer Company,[13] one with C. G. Conn, Ltd.,[14,15] and one with Princeton University.[16-23] As a result of preliminary work under these contracts, the following facts became apparent, making cessation of work on subcarriers by Wurlitzer and Conn appear desirable.

There are essentially two methods of telemetering:

1. Subcarriers (continuous system).
2. Commutation (intermittent scanning).

A general discussion of both methods is presented. The following is a comparison of the requirements on the radio link and associated circuits.

Subcarriers (1) A high degree of linearity of radio link and associated circuits is required to avoid cross talk. For example if x per cent of third harmonic distortion is present, $6x$ per cent cross modulation appears. The situation is worse for higher harmonics. This makes choice of center frequencies difficult.

2. There is no stringent requirement as to frequency response as long as it does not vary appreciably over the pass band of any channel.

Commutation. (1) Linearity of radio link and associated circuits need be of sufficient degree for reduction of data. If calibration curves are used, linearity is relatively nonessential.

2. In order to avoid cross talk, the frequency response of the radio link must reproduce the composite signal adequately. This is discussed in the body of the report.

1.5 NOISE CONSIDERATIONS

Theoretical considerations have shown that commutation has advantages over subcarriers with respect to both fluctuation and impulse noise.[21] This advantage is more pronounced as the number of channels is increased. The reason is that in commutation each channel occupies the whole modulation range, whereas this range must be divided among the subcarriers requiring considerable separation between them in the frequency selector.

The choice between subcarriers and commutation will depend upon the number of channels, required frequency response of each channel, required intelligence-to-noise ratio, nature of radio link at hand, etc. If a number of slowly varying channels are to be handled, it appears that commutation, mechanical or otherwise, has advantages in equipment and performance. If merely a few rapidly varying channels (frequency response to 150 c, for example) are required, it is difficult to estimate from theoretical considerations alone which system would be better. If 20 or more channels are needed, it appears that commutation has advantages as to intelligence-to-noise ratio and as to linearity requirements of the radio link and associated circuits.

It is suggested that in the case where reactance gauges, such as reactance accelerometers, can be used, some improvement in signal-to-noise ratio can be obtained if sufficient band width is available. This is accomplished by using the reactance gauge to modulate the frequency of the subcarrier oscillator and by using a limiter and a discriminator after the frequency selector at the receiving end, i.e., subcarrier frequency modulation.

Both general methods of telemetering have been tested under diverse requirements and conditions by various organizations. A brief summary of the work of these organizations is included in this report. The general consideration of subcarriers vs commutation might be summarized as follows: Multiplexing by subcarriers demands good linearity of the transmitting medium from an amplitude standpoint, to prevent intermodulation between the various subcarriers, but does not demand good frequency response, since the relative amplitudes of the subcarriers are unimportant. However, commutation demands good frequency response to avoid distortion of the square pulses derived from the switching circuits and corresponding cross talk between channels, but amplitude nonlinearity will not cause intermodulation between channels although it will cause nonlinearity of any given channel. The latter can be removed by calibration of each channel. In general, a radio link can be made relatively satisfactory from a frequency-response standpoint, but is difficult to make linear to a wide range of amplitudes. Accordingly, commutation lends itself to multiplexing via radio link, in numerous cases producing more satisfactory results than subcarrier multiplexing.

1.6 DESCRIPTION AND TECHNICAL INFORMATION

1.6.1 General Discussion

For the flight testing of aircraft it is often desirable to transmit data, such as instrument readings, strain-gauge and accelerometer indications, etc., via a radio link to a ground station where the data can be recorded. This process is generally referred to as telemetering. In this report each individual sequence of data (e.g., information from a particular strain gauge) is called a channel. It is generally desired to tele-

meter a number of channels. On account of power, space, weight, antenna, and other considerations, it is usually undesirable to provide a separate radio link for each channel. It is, therefore, necessary to provide some means of transmitting a number of channels over the same radio link. Figure 1 is a generalized block diagram of a telemetering system for transmitting and recording n (see Section 1.7) channels of information.

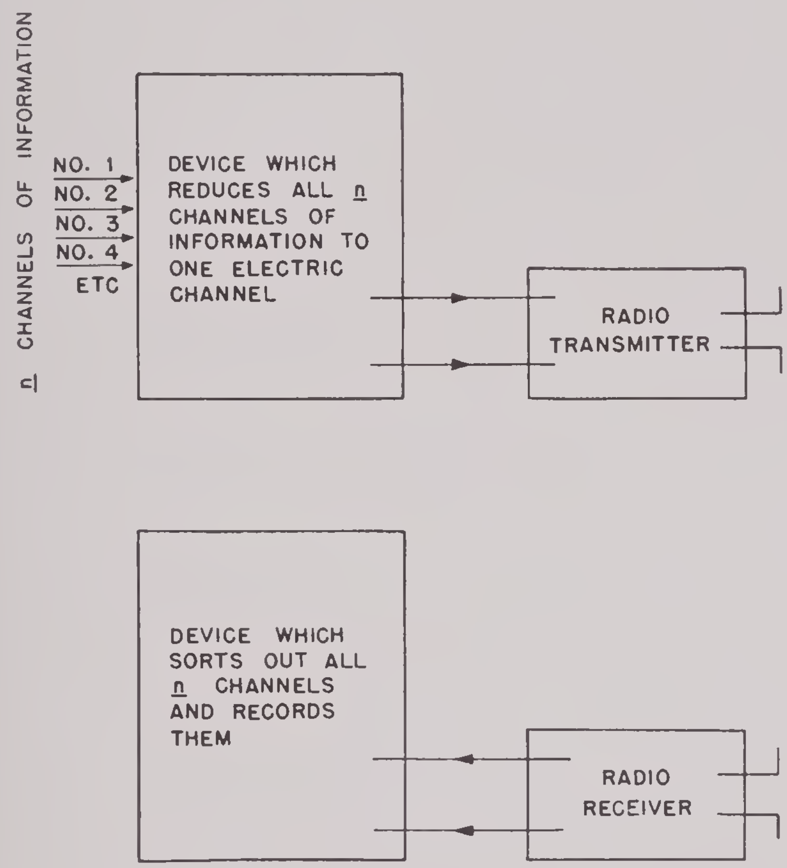

FIGURE 1. Block diagram of basic telemetering system.

The device which reduces the n channels to one electric channel to modulate the radio transmitter may be a subcarrier system, a commutator, either electric or mechanical, a television-scanning device, or a combination of all three. The corresponding receiving device which records all channels will be a frequency selector and recorder, if subcarriers are used; a synchronized commutator and recorder (for slow commutators a recorder is sometimes sufficient), if commutation is used; a television screen and movie camera, if television is used; or a combination of all three.

There are essentially two methods by which telemetering can be performed: these two methods are the subcarrier systems and the commutation systems.

Subcarrier Systems

A separate subcarrier frequency is provided for each channel. This is usually in the range from 1 to 50 kc, and is called a subcarrier because the range is much lower in frequency than the radio carrier. This subcarrier is modulated, either in amplitude or in frequency, with the information of the channel. Most systems use amplitude modulation. The subcarriers are then linearly superimposed (mixed) and transmitted by radio to the receiving station. There the various subcarriers are selected, amplified, detected, and fed to the recording instrument. The frequency selection can be accomplished in several ways.

Ordinary Subcarrier System. A separate band-pass filter is used for each subcarrier, the frequency of the subcarrier being adjusted to the center of the pass band. The band-pass filters are usually designed to operate in parallel. Figure 2 is a block diagram of this method.

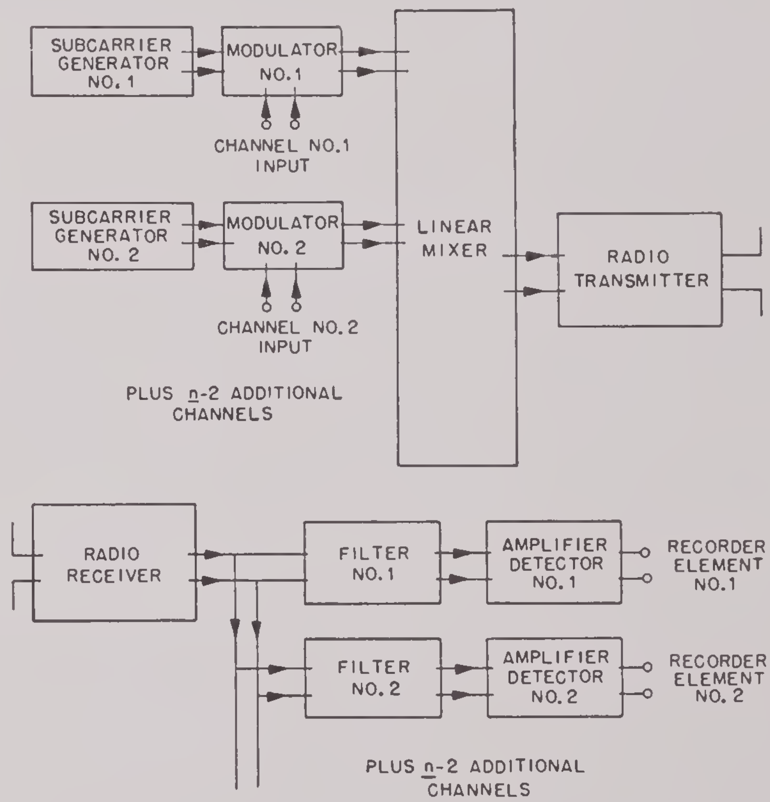

FIGURE 2. Block diagram of subcarrier telemetering system for n channels using n band-pass filters.

Heterodyne Subcarrier System. At the receiver, each channel is provided with a local oscillator which beats against its corresponding subcarrier to give a certain frequency which is approximately in the center of a band-pass filter. Thus n identical band-pass filters can be used instead of the n different filters required in the

ordinary method. The output of each filter is then amplified, detected, and fed to its recording instrument. Figure 3 is a block diagram of the receiving part of this system. The transmitting part is identical with Figure 2.

The Wattmeter Principle. The conventional wattmeter has a current coil and a voltage coil.

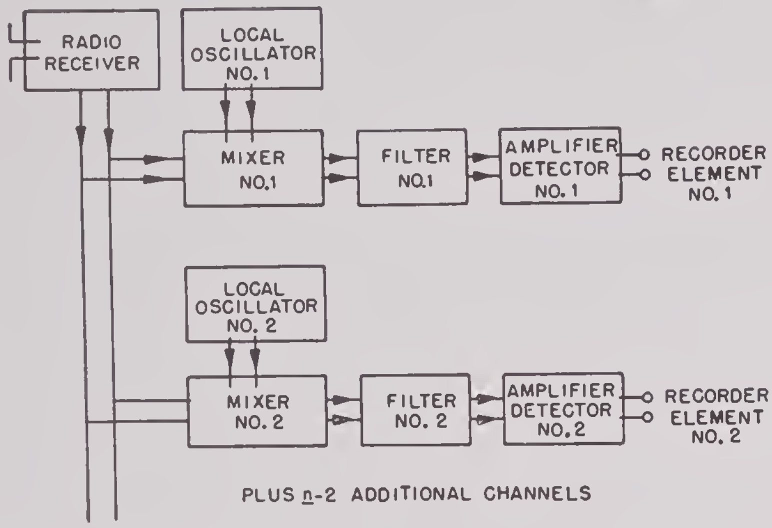

FIGURE 3. Block diagram of receiving portion of heterodyne subcarrier system.

If the period of the meter is long compared to the periods of the current and voltage, the reading of the meter is proportional to the time average of the product of the current times the voltage, i.e., proportional to the time average of the product of the currents through the coils. For the purpose of frequency selection, one wattmeter would be provided for each channel. In the case of a single channel, e.g., the mth one, the composite signal from the radio receiver would be applied to one coil of the wattmeter, and a signal from a local oscillator of constant amplitude and of the same frequency as the mth subcarrier would be applied to the other coil. If the period of the wattmeter is long compared to that of the subcarrier but short compared to that of the modulation, the reading of the meter, which is proportional to the time average of the product of the two signals applied to the coils, would be proportional to the amplitude of the mth subcarrier times the cosine of the phase angle between the mth subcarrier and the mth local signal. All other subcarrier frequencies average out. Figure 4 is a schematic diagram of the wattmeter frequency selector. The transmitting circuit is the same as that of Figure 2. Care must be taken to keep the amplitude of the local oscillator constant and the phase angle between corresponding subcarriers and local oscillators the same. This means that the corresponding frequencies must be exactly equal.

In practice, the wattmeter, a square law device, is not used; instead, electric circuits, which achieve the same results, are employed. These circuits make use of a nonlinear device which gives the product of the local generator signal and the composite signal from the radio receiver. By means of balanced circuits, filters, etc., it is possible to select the desired frequency.

Frequency-Modulated Subcarrier System. There is at least one system in use in which the subcarriers are frequency-modulated. Each subcarrier oscillator has a variable reactance in the tank circuit which modulates the natural frequency of the oscillator. This reactance is controlled by an accelerometer, strain gauge, or other device. It is convenient to make the frequencies of the subcarrier oscillators rather high (order of 100 kc) so that the frequency deviation may be several per cent.[21b]

In general, the use of frequency-modulated subcarriers with the resistance strain gauges requires amplification to a relatively high level,

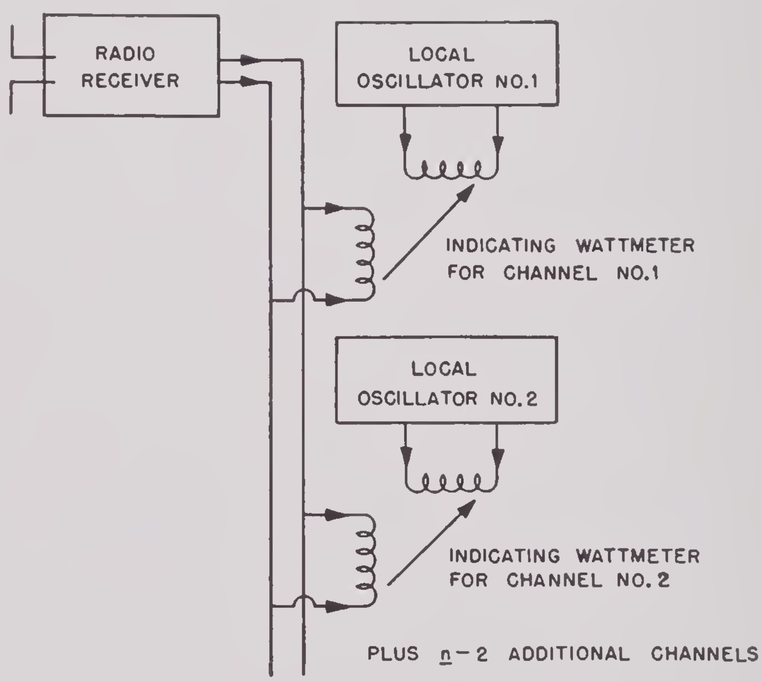

FIGURE 4. Block diagram of wattmeter method of frequency selection.

plus frequency modulation by means of a reactance tube or phase modulator. However, with these types of modulation it is difficult to obtain a high deviation ratio. Reactance-type strain bridges can be used conveniently only in special cases because of their size, accurate machining

required, dependence upon vibration, etc. Also a considerably larger band width is required to handle the frequency-modulation side frequencies.

The receiver consists of a frequency selector and a limiter and discriminator for each channel. The results are good only if the signal strength is great enough to saturate the limiters.

Operation and Limitations of Subcarrier Systems. For specific purposes the subcarriers may be modulated in many ways. One common example is the application to a strain-gauge bridge in a particular channel. The input of the bridge is usually the subcarrier frequency of that channel and the output of the bridge is then the subcarrier frequency amplitude-modulated in proportion to the strains. Another example is an accelerometer the amplitude of which modulates the subcarrier in proportion to the acceleration.

The following requirements must be met for the application of the subcarrier systems:

1. *Linearity of radio link.* All circuits from the transmitter input to the mixer to the filter input at the receiver must be linear to avoid cross modulation. Let the subcarrier frequencies be f_1, f_2, $f_3 \cdots f_n$. Let the response of the link from the input of the mixer, v_i, and its output to the receiver frequency selector, v_o, (assuming the frequency selector to be linear) be related by the power series

$$v_o = a_1 v_i + a_2 v_i^2 + a_3 v_i^3 + \cdots + a_\beta v_i^\beta, \qquad (1)$$

If there is complete linearity, all a's except a_1 are zero. If the link is nonlinear, various powers of v_i appear with coefficients which depend upon the nature of the nonlinearity. The effect of nonlinearity is to introduce various modulation products resulting in the generation of new frequencies which are the sums of various linear combinations of the subcarrier frequencies. It can be shown that the new frequencies introduced by each term of equation (1) are given by all possible combinations of the sum

$$m_1 f_1 \pm m_2 f_2 \pm m_3 f_3 \pm \cdots \pm m_n f_n \qquad (2)$$

in which the m_j's are positive integers including zero, such that

$$\sum_{j=1}^{j=n} m_j = \beta \qquad (3)$$

in which β is the power of v_i in the particular term of the power series of equation (1). Table 1 gives the frequencies which are generated by nonlinearity for values of β up to 4. For this table only unmodulated subcarriers are considered and the amplitude of each is set to unity. The a_j's are the coefficients in equation (1).

Take for example a certain subcarrier system having frequencies 10,833 to 43,333 in steps of 2,500 c.

Table 1 gives the cross-modulation frequencies generated by the term in the power series of equation (1) whose exponent is β. Consider the effect of the nonlinearity which brings in only the first and second powers of v_i. Table 1 shows

TABLE 1

Amplitude relative to βth harmonic	β	Amplitude	Cross-modulation frequencies
1	1	a_f	$f_1, f_2, f_3 \cdots f_n$
1	2	$1/2a_2$	$2f_1, 2f_2, 2f_3, 2f_4, \cdots 2f_n$
2		a_2	$f_1 \pm f_2, f_1 \pm f_3, \cdots f_1 \pm f_n$; $f_2 \pm f_3, f_2 \pm f_1, \cdots f_2 \pm f_n$; etc.
9	3	$9/4a_3$	$f_1, f_2, f_3, \cdots f_n$
1		$1/4a_3$	$3f_1, 3f_2, 3f_3, \cdots 3f_n$
3		$3/4a_3$	$2f_1 \pm f_2, 2f_1 \pm f_3, \cdots 2f_1 \pm f_n$; $2f_2 \pm f_1, 2f_2 \pm f_3, 2f_2 \pm f_n$; etc.
6		$3/2a_3$	$f_1 \pm f_2 \pm f_3, f_1 \pm f_2 \pm f_4, \cdots f_1 \pm f_2 \pm f_n$; $f_1 \pm f_3 \pm f_4$; etc.
16	4	$2a_4$	$2f_1, 2f_2, \cdots 2f_n$
1		$1/8a_4$	$4f_1, 4f_2, \cdots 4f_n$
36		$9/2a_4$	$f_1 \pm f_2, \cdots f_1 \pm f_n$; $f_2 \pm f_3, \cdots f_2 \pm f_n$; etc.
6		$3/4a_4$	$2f_1 \pm 2f_2, \cdots 2f_1 \pm 2f_n$; $2f_2 \pm 2f_3, \cdots 2f_2 \pm 2f_n$; etc.
4		$1/2a_4$	$3f_1 \pm f_2, \cdots 3f_1 \pm f_n$; $3f_2 \pm f_1, \cdots 3f_2 \pm f_n$; etc.
12		$3/2a_4$	$2f_1 \pm f_2 \pm f_3, \cdots 2f_1 \pm f_2 \pm f_n$; $2f_1 \pm f_3 \pm f_4, \cdots 2f_1 \pm f_3 \pm f_n$; etc.
24		$3a_4$	$f_1 \pm f_2 \pm f_3 \pm f_4, \cdots f_1 \pm f_2 \pm f_3 \pm f_n$; etc.

that there are cross-modulation frequencies which are double all subcarrier frequencies, giving 21,666; 26,666; 31,666; etc. These frequencies lie not closer than 833 c from the center frequencies of the subcarriers. In this particular system the frequency selector is down about 20 db for 800 c off center frequency. Unless a_2 in the power expansion of equation (1) is large, these double frequencies will consequently not cause much trouble. There are also cross-modulation frequencies representing all sum and difference frequencies, taken two at a time. This gives $10{,}833+13{,}333=24{,}166$; $10{,}833+15{,}833=26{,}666$; etc. Inspection shows that these also are at least 833 c off center frequency.

Now consider $\beta = 3$. There are cross-modulation frequencies which are three times the subcarrier frequencies, giving 32,499; 39,999; etc. These frequencies are at least 834 c off center frequency. Also there are all frequencies plus or minus twice all other frequencies taken two at a time, giving $33{,}333 - 2 \times 10{,}833 = 11{,}667$; $35{,}833 - 2 \times 10{,}833 = 14{,}167$, etc. These are at least 834 c off center frequency. But there are also all sums and differences, taken three at a time giving, for example, $10{,}833 + 15{,}833 - 13{,}333 = 13{,}333$; $13{,}333 + 15{,}833 - 10{,}833 = 18{,}333$. These are exactly on the center frequencies of the various subcarriers. Thus, if the subcarriers are modulated, it is possible for the modulation to cross from one channel into another without being attenuated by the frequency selector. Furthermore, Table 1 shows that if there is n per cent third harmonic distortion, there results from the $a_3 v_i^3$ term $6n$ per cent cross modulation without attenuation. For higher values of β there are more complicated linear combinations of the various frequencies which could cause cross modulation in many ways.

From Table 1 it can be seen that, for a given value of β, the modulation sums have larger amplitudes than the harmonics. It is therefore generally more important to arrange the center frequencies of the filters to exclude these modulation sums than to arrange them to exclude merely the harmonics. As larger numbers of subcarriers are used, this becomes more difficult, so that accurate linearity of the radio link, etc., becomes imperative.

2. *Modulation of radio link.* Figure 5 gives the output voltage versus input voltage for a typical frequency-modulation radio link. It is reasonably linear over a finite input voltage range. In order to avoid operation in a badly nonlinear portion, the input voltage must never exceed a certain value. If the link is to be used to transmit sub-

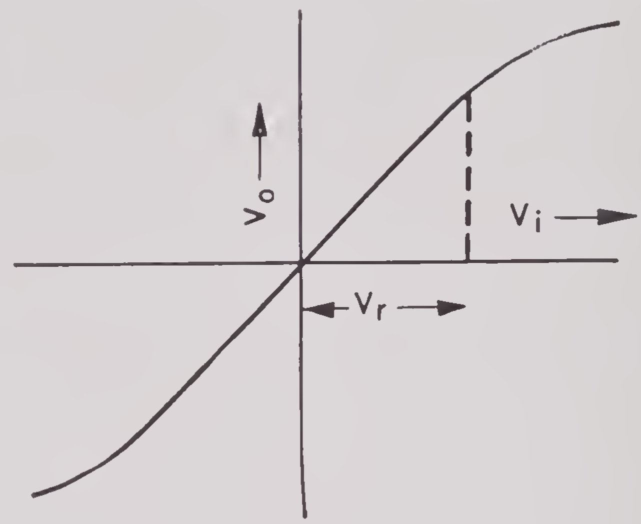

FIGURE 5. Output voltage versus input voltage for typical f-m radio link.

carriers without the possibility of cross modulation, the sum of the instantaneous voltages of all the subcarriers must never exceed this definite value. Let the linear input voltage amplitude range be V_r. If each subcarrier is not to be modulated more than 100 per cent, and, if all subcarriers are operated at the same amplitude, then the unmodulated amplitude of each subcarrier must not exceed $V_r/2n$. If there is a relatively large number of subcarriers not more than 100 per cent modulated, the likelihood of all of them adding up at any one time to give a maximum voltage is rather small because of random phases, etc.[d,25,26] However, if an indicating instrument should break, a strain-gauge bridge tear off, or the like, it is conceivable that a given subcarrier might reach a large amplitude unless suitable limiting devices are applied (as, for example, a limiter tube similar to frequency-modulation limiters). However, limiters generally bring in harmonics. If the frequency selector is such that these harmonics would cause trouble, this can be remedied by putting the output of each limiter through a filter, which is placed between the limiter and the mixer at the transmitter, and

[d] This is an important subject in subcarrier telephony. There the situation is somewhat improved by single sideband transmission, allowable occasional cross modulation, etc.

which removes harmonics. Figure 6 is a block diagram of such a device. A possible alternative limiter is outlined later in connection with the work of the Rudolph Wurlitzer Company. (See Section 1.6.2.)

In the case of several subcarrier systems under development and in use, no provision for limitation is made because it is felt that periods of overmodulation will be so rare as to be unimportant.

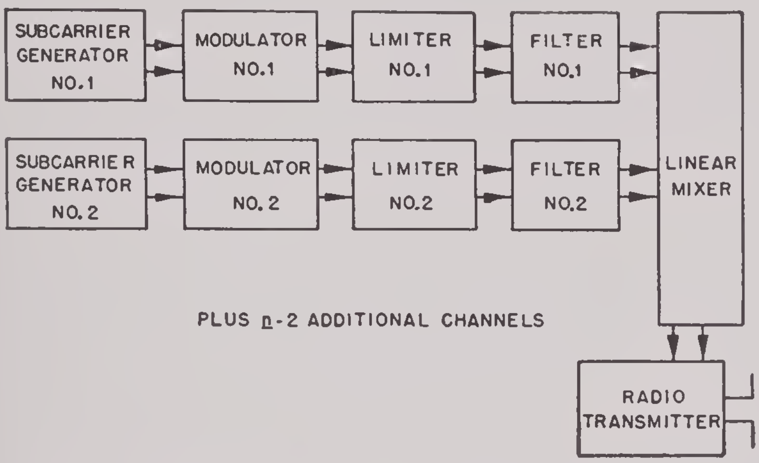

FIGURE 6. Block diagram of circuit to prevent overmodulation by use of limiters.

3. *Frequency stability of subcarriers.* The subcarrier frequencies must be stable enough to keep the center frequencies and side bands inside the "horizontal" portion of the pass bands of the frequency selector. Also, the subcarrier amplitudes must be kept constant to within the required accuracy of the apparatus.

4. *Phase discrimination.* Consider an indicator such as a balanced strain-gauge bridge, driven by a particular subcarrier frequency. The only difference in the output between off balance on one side and off balance on the other is that one is 180 degrees out of phase with respect to the other. Thus, unless provision is made at the receiver for phase discrimination, there is no way of telling on which side the bridge has changed. Since a great deal of extra apparatus is required to give the time reference for phase discrimination, it is not provided. Therefore, the bridge is operated so that during the measurement the balance point is never passed through and the bridge is continuously operated off balance on one side. Off-balance operation requires twice the output amplitudes to yield the same accuracy as would be obtained with phase discrimination. Thus off-balance operation is not so economical as far as the use of the available linear range of the radio-transmission link is concerned.

5. *Bridge balancing.* In order to accommodate a large number of subcarriers with the same radio link, it is necessary to go to high subcarrier frequencies such as 40 or 50 kc. At these frequencies the problem of the capacity balance of the bridges often becomes more difficult because of long connected cables. This requires cables with distributed capacitance and dielectric loss adequately independent of temperature, pressure, etc.

Commutation Systems

The principle of commutation is to sample or to scan a number of channels in sequence, thus reducing n channels to one electric channel for radio transmission. Figure 7 is a schematic dia-

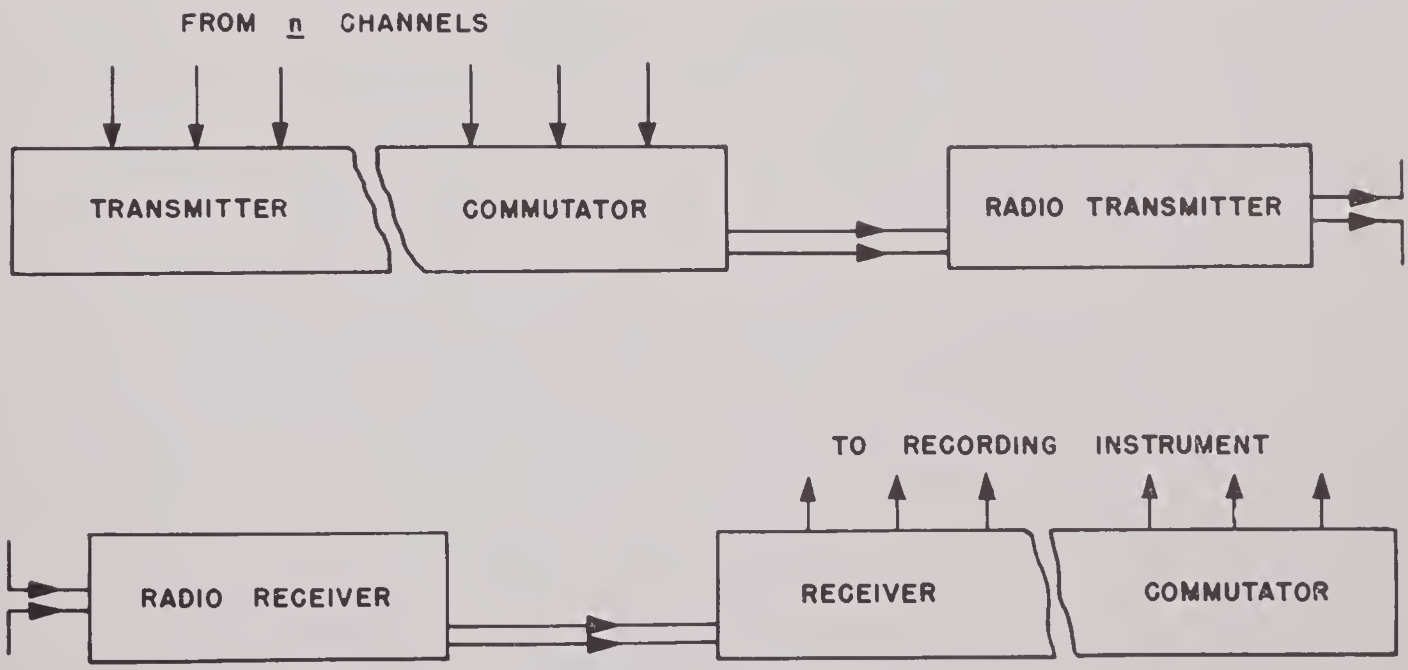

FIGURE 7. Commutation telemetering equipment.

gram of commutation telemetering equipment.

Since the transmitter commutator samples each channel, provision must be made at the receiver to recreate the intelligence in each channel from the samples transmitted for that channel. Smooth sine waves can be reproduced very easily from ten samples per cycle. It can be shown that if ideal vertical filters could be used, a maximum frequency response of one-half the number of samples per second could be realized by an electric integrator.[21a] For visual interpretation it is *convenient* to have about ten samples per cycle although a *systematic* interpretation would require fewer samples. The reproduction may be done electrically with suitable circuits, mechanically, or by drawing smooth curves through recorded points.

During the time a given channel is sampled, its intelligence can fill the complete modulation range of the radio link. This is an important property of commutation as opposed to subcarrier systems, in which each channel can occupy, on the average, only $\frac{1}{2}n$ of the modulation range.

Several distinct systems of commutation have been developed.

Television. In the broad sense, television is a commutation system because each portion or slice of a picture is scanned about 40 times per second, which is the framing speed of present-day television (Block III). In this system an instrument panel containing altimeter, bank and turn, tachometer, etc., is televised and photographed by movie camera at the ground station. There are many other methods of indicating data, such as projecting light spots from galvanometer elements on the instrument panel so that they may be televised. It is, therefore, possible to get about 40 samples per second (the television framing speed) for each of the many channels of information. From 40 samples per second the theoretical maximum-frequency response from the most systematic interpretation possible is $40/2$ c $= 20$ c.[14] It has been found that about *six* samples per cycle are required for convenient interpretation. Thus a practical frequency response is $40/6 = 6$ c. In some systems as many as 48 galvanometer spots plus a half-dozen flight instruments and 15 breakage indicator lights are used. (See Curtiss-Wright systems under Section 1.6.2.) However, television is not efficient because for a given set of data only a small portion of the instrument panel is used for the indication and therefore many scanning strokes are wasted. For example, one system of television uses 15,750 scanning strokes per second and produces 30 frames in that time. If each stroke were made to indicate one channel of information, this would give $15{,}750/30 = 525$ channels sampled 30 times a second, as compared with about 50 channels which are televised at present. Thus, television makes use of only 10 per cent of its capacity. The job of reducing the data from 30 to 40 frames of movie film for every second is a tedious one and the space (including that for optical equipment), weight, and power required for television are formidable. Against these considerations must be weighed the fact that television apparatus is in mass production and can be obtained for flight-testing purposes. Also, it is likely that in some cases it is desirable to reproduce an optical image of flight instruments, for example, to observe their behavior during maneuvers, observe the horizon, etc. For remote-control purposes it may be desirable for the operator to observe a set of instruments which give the common variables such as airspeed, altitude, engine revolutions, bank and turn indicators, etc.

This means that improvements as to space, weight, power, etc., should be made in television apparatus so that it may be used where necessary. Also, more compact and efficient apparatus for handling slowly varying channels, now handled by television, should be developed from approaches which do not have the fundamental limitations of this system. At the receiving station, other systems have the advantage that they can be made to operate, for example, electric meters, which are laid out to resemble flight instruments (see Section 1.6.2), as well as to operate continuous recording apparatus.

Direct Commutation. Figure 8 is a schematic block diagram of a transmitting commutator. Each valve (e.g., a relay, an electronic tube, or the like) is turned on and off in sequence. The outputs of all valves are connected in parallel. First, all valves are off; then No. 1 valve is turned on, allowing information only from channel No. 1 to flow into the transmitter. After one switch-

ing period, No. 1 is turned off and valve No. 2 is turned on, which allows information from only channel No. 2 to flow into the radio transmitter. This process is continued until all n channels

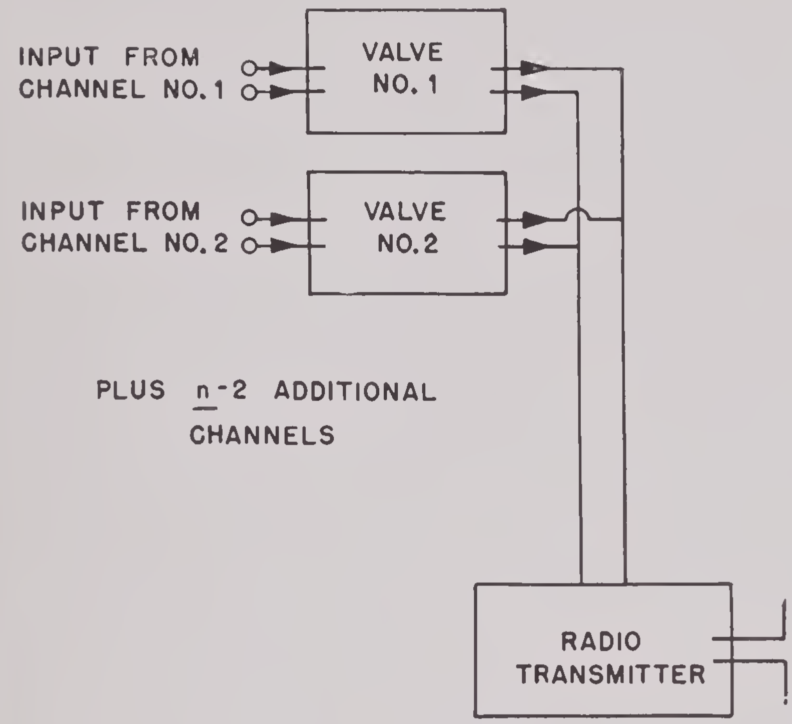

FIGURE 8. Block diagram for transmitting commutator.

have been sampled and the sequence starts over again.

The output of the transmitter commutator which feeds into the transmitter might appear somewhat as in Figure 9A, in which four channels are indicated. The intelligence in each channel may be carried by the amplitude or the frequency of the signal sampled from that channel. The frequency of each channel relative to the commutation may be such that the sampling covers many cycles or only part of a cycle.

At the receiver the channels may be "sorted out" and recorded separately or the output of the radio receiver may be recorded directly and the channels sorted out later, either automatically or otherwise. If the channels are sorted out before recording, there must be some form of receiver commutator which is synchronized with the transmitter commutator so that when valve No. 1 in the transmitter is open, valve No. 1 in the receiver is open, etc. (see Figure 9B). The synchronization may be carried out by means of synchronizing pulses transmitted along with the intelligence (as is done in television, for example).

As noted before, the samples per second must be somewhat greater than twice the highest frequency to be reproduced. If there are n channels to be sampled F times per second, the switching speed must be nF per second. The quantity nF determines the method of commutation that can be used. Several systems will be discussed later.

Subcommutation. Several installations now in use consist of a number of high-frequency channels telemetered by radio and a number of slowly varying channels telemetered by television. As mentioned before, apparatus which is smaller, lighter, and requires less power can be used for handling slowly varying channels for certain types of flight testing where optical reproductions of flight instruments are not required. In the case of commutation these slow channels could be handled by subcommutation. Figure 10 is a block diagram illustrating a simple form of a subcommutation system. Each subcarrier channel is indicated in the shape of a strain-gauge bridge, but may be any type of modulating device. The switching frequency of the low-speed valves is the sampling frequency of the high-speed valves, so that after each sequence of these, the low-speed valves switch the excitation to the next column of bridges. The advantage of the square array is that it reduces the number of valves (amplifiers, etc.) required. In general, if the square contains x channels per

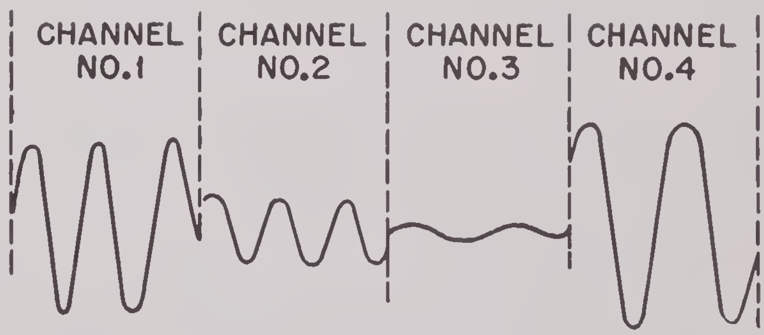

FIGURE 9A. Diagrammatic output of transmitter commutator for four channels.

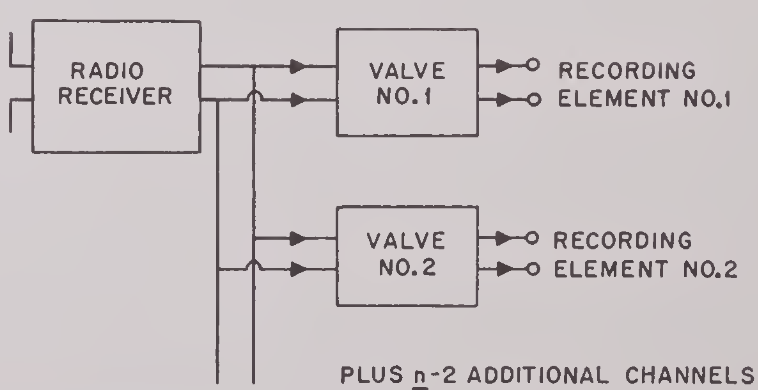

FIGURE 9B. Block diagram of receiver commutator.

side, x^2 subcommutator channels can be sampled with $2x$ valves. This becomes important as x gets larger. For example, 49 subcommutator channels could be handled with 14 valves.

Many other arrangements of subcommutator systems are immediately obvious. It would probably be desirable to make the subcommutator a part of the high-speed commutator by devoting several high-speed channels to this purpose, thus making possible the use of the same radio transmitter. The types to be used should depend upon the number of commutation channels to be handled, the number of high-speed channels to be devoted to this purpose, space available, etc. At the receiver the channel signals can be sorted out by a similar, synchronized subcommutator. They can then be recorded or, for example, they can be made to operate electric meters laid out to simulate standard flight instruments, etc.

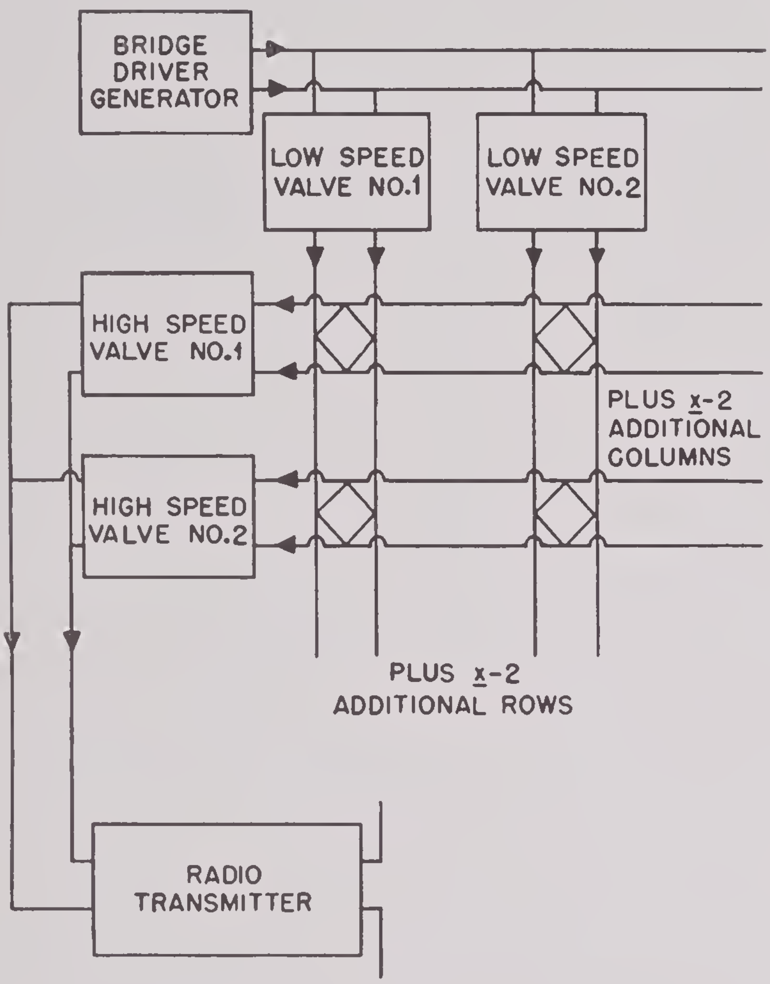

FIGURE 10. Block diagram of subcommutator system for many slowly varying channels.

Operation and Limitations of Commutator Systems. (1) *Frequency response of radio link.* The frequency response of the link between the two commutators must be good enough to reproduce the signal from the transmitter commutator. Suppose that each valve of the commutator is sampling a signal which varies slowly enough and that the switching from one valve to the next is instantaneous, so that the output of the transmitter commutator appears as in Figure 11A. In order for 11A to be reproduced accurately over a radio link, the frequency response of the link must be high enough to reproduce the sharp corners. For purposes of discussion let the audio band of the radio link be as an ideal low-pass filter with a sharp cutoff at frequency F_a. If this cutoff, F_a is not high enough, the corners of Figure 11A will be rounded somewhat, as in Figure 11B. The higher (or lower) the adjacent channel, the more the rounding. Thus intelligence from one channel can "spill over" into nearby channels, resulting in cross talk. One way to reduce this spilling effect is to insert gaps between the channels as in Figure 11C, in which the dashed lines gives the pattern with ideally high-frequency response and the solid line the pattern with somewhat lower F_a. The dotted vertical lines represent the time division between channels. The gaps, or blank spaces, thus reduce the cross talk if the

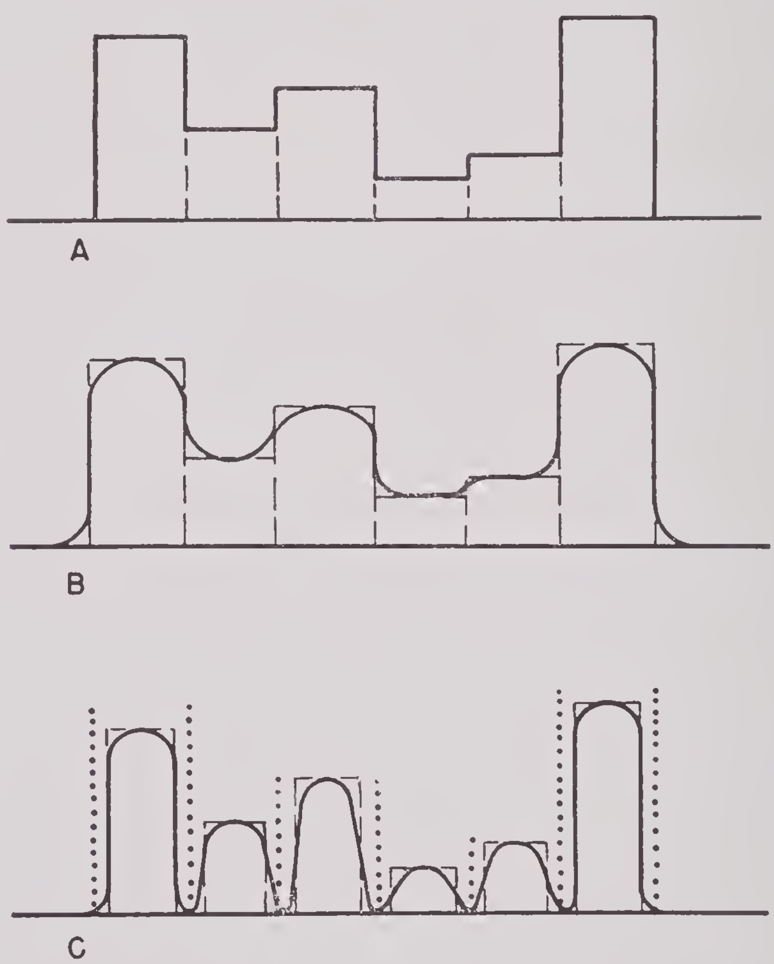

FIGURE 11. Commutator response requirements.

rounded parts of the adjacent channels do not cross the dotted lines. This rough illustration is to give an idea of the effect of the finite frequency response of the link.

The important question is how large must F_a be in order to reduce the cross talk to the required minimum. The theory and calculations required to answer this question are somewhat complex, although standard. Consequently, numerical results based on a paper by W. R. Bennett[27] are stated as follows. Let corresponding channels at transmitter and receiver be on for $1/\alpha$ of their allotted time, i.e., $1/\alpha$ of the time interval $1/nF$. Also, let the output from the transmitter commutator be the same type as in the dashed lines of Figure 11C. Figure 12 is a plot of the cross-talk suppression to adjacent channels for a set of 20 commutator channels plotted as a function of the upper limit F_a of the radio link in terms of the sampling frequency F (i.e., the ordinate gives the db down between channels if the low pass were cut off sharply between the integral multiples of the sampling frequency on the corresponding abscissa).[14] However, the cross-talk suppression to *any* channel cannot be less than the minima in the curves of Figure 12 regardless of how the low pass is cut off or regardless of overlapping of side-band pairs ($f >> F/2$). Also the square corners of Figure 11 require a higher frequency response than rounded ones, such as portions of sine waves. Figure 13 is a plot of cross talk for various α's, made by drawing a curve through the minimum points on curves such as those in Figure 12. Figure 13 applies to 20 channels. However, if ten channels were used, approximate results would be obtained by dividing the abscissa values by two. If 40 channels were used, the abscissa values should be multiplied by two and the approximation would be more accurate the larger the number of channels. Thus, from the point of view of cross talk and minimizing of F_a, if 50 db down (or more) is required, it is better to use values of $\alpha = 3$ or more. If something of the order of 40 db down is required, values of α near unity are better.

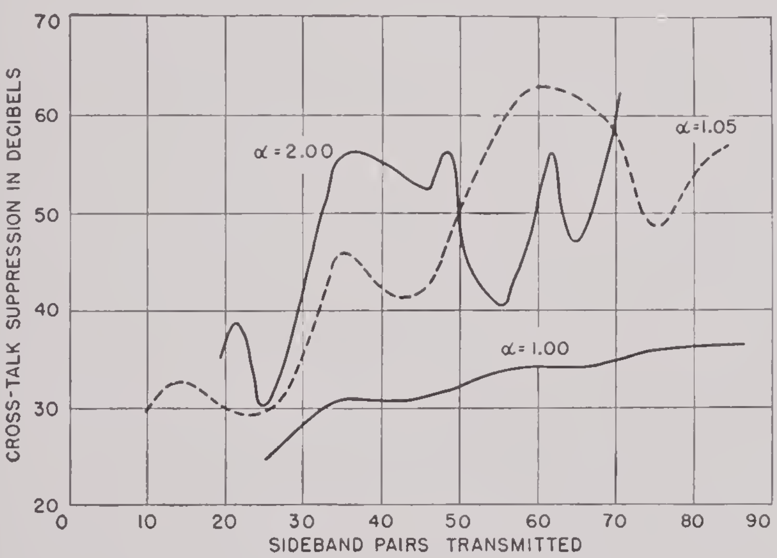

FIGURE 12. Actual cross-talk suppression versus radio-link frequency characteristics—20-channel commutation.

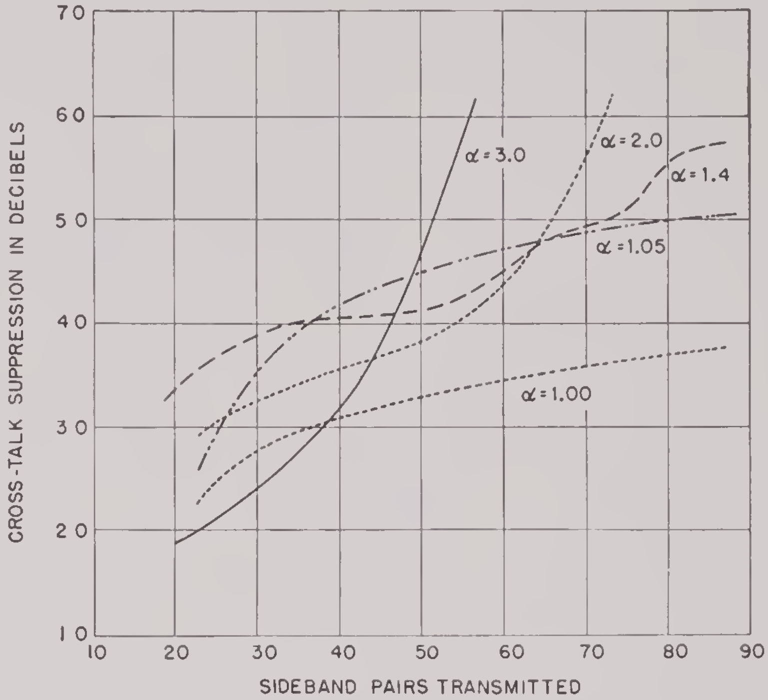

FIGURE 13. Minimum cross-talk suppression versus radio-link frequency characteristics—20-channel commutation.

Suppose that large values of α are used and that a low-pass cutoff F_a could be arranged to cut off sharply between adjacent side-band pairs which requires that $f < F/2$. It can be shown that if an odd number of channels is used, giving the proper phasing of frequency components, the cutoff frequency F_a can be made quite small. For example, with 21 channels the minimum cutoff F_a could be between the tenth and eleventh side-band pairs, resulting in the following table for cross modulation as a function of α:

α	db down
3.0	35
5.0	43
7.5	50

It is also possible to cut off between certain higher adjacent side-band pairs with somewhat better results.

2. *Linearity of radio link.* Since each channel can occupy the whole modulation range during the time it is sampled, the link between the input to the channels and the output to the recording instrument need be only as linear as is necessary for the type of measurement to be performed. If the technicians reducing the data are willing to work from calibration curves, the link can be somewhat nonlinear. Overmodulation of any channel causes no difficulty in any other channel provided the frequency response of the link is adequate to reproduce the transmitter commutator output without spilling from one channel to the next. In other words, overmodulation does not result in cross talk of the nature inherent in subcarriers.

3. *Synchronization.* If a receiver commutator is used, positive synchronization with the transmitter commutator must be provided. In case of fading or other interruption, the synchronization must be readily restored as soon as the radio link again becomes operative. The only way to achieve this is through the use of synchronizing pulses carried by the radio link or transmitted over an auxiliary link.

4. *Signal generator.* Only one master device at the transmitter end is required to operate the valves and to insert the synchronizing pulses into the transmitted signal. This same device can also be used to excite the bridges, etc. Since the receiver commutator is tied in by the synchronizing pulses, timing of the master device is not critical.

5. *Bridge-voltage supply.* The amplitude of the bridge-driving frequency must be held constant to within the required accuracy of the apparatus, etc.

Combinations of Subcarrier and Commutation Systems

When a number of channels to carry slowly varied signals is required, a combination of subcarrier and commutation systems can be used. Numerous combinations are possible, but only one will be mentioned here. This system is very similar to the subcommutation in Figure 10 and is shown schematically in Figure 14. Subcarrier frequency generators continuously excite the columns of bridges. (Any other form of modulator could be used.) The commutator valves sample each row of bridges in sequence. The receiving apparatus consists of a commutator, synchronized with the transmitter commutator, and a frequency selector. These act essentially in the reverse order to the transmitter commutator.

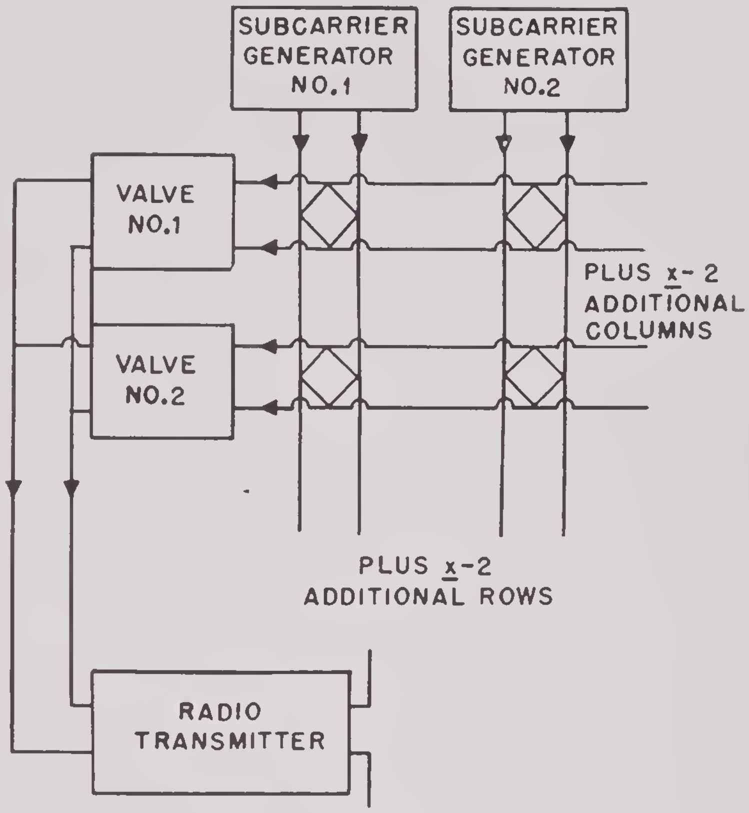

FIGURE 14. Block diagram of subcarrier commutation system for many slowly varying channels.

In this system the switching rate must not be so great that the pass bands of the receiver frequency selectors are not adequate; otherwise the commutated channels of the same subcarrier frequency will spill into each other. The square array has the advantage of handling a large number of channels with a minimum number of valves, subcarriers, amplifiers, etc., as previously explained.

A combination of this nature could be incorporated into a system of subcarriers which carries rapidly varying channels, making possible the use of the same radio link for both rapidly and slowly varying channels.

1.6.2 Summary of Telemetering Systems in Use and under Development

In this section some of the various systems recently developed for aircraft telemetering are described briefly. They are designated by the names of the companies or organizations by which they were developed. It is to be understood that in most cases the data given are for experimental models. Considerable improvement in

space, weight, power, etc., may be realized when the apparatus is engineered for the final models.

SUBCARRIER SYSTEMS

Curtiss-Wright Corporation, Buffalo, New York. The Curtiss-Wright equipment for structural flight testing consists of radio and television-telemetering systems, synchronously connected. The former has 14 amplitude-modulated subcarriers for channels requiring uniform (± 0.5 db, or about ± 5 per cent) frequency response up to 200 c. The television system transmits an image of a panel on which are mounted six flight instruments and a screen upon which are projected light spots from 48 galvanometer elements. The television is used for transmitting data on strains, pressures, temperatures, position of control surfaces, etc., which are not expected to vary at a rate exceeding approximately 8 c. The work was carried out under Navy Contract NOa(S)991.

The subcarrier system is a 14-channel heterodyne type (see Section 1.6.1). The subcarrier frequencies are 10,833 to 43,333 in steps of 2,500 c.[e] Pertinent data are as follows:

1. Airborne apparatus.
   a. The 14 subcarrier oscillators are of the LC type with compensated feedback to assure amplitude stability. The coil and condenser combination used showed good frequency stability.
   b. The outputs of the oscillators are fed through transformers to strain-gauge bridges. Their outputs in turn are mixed through buffer amplifiers with a common plate resistance and then fed to the transmitter through a master amplifier.
   c. The number of tubes per channel is three.
   d. The approximate volume of the airborne equipment, exclusive of the power supply and radio transmitter, is 2¼ cu ft and its weight 55 lb. The weight of the total equipment is 144 lb.
   e. Excluding the radio transmitter, the B power requires 350 ma at 250 v, electronically regulated from a 400-v genemotor. The heater requires 7 amp at 22 v. The overall power requirement, including the needs of the transmitter, is 28 amp at 22 v direct current, regulated from the airplane's 28-v direct-current power supply.
2. Radio link.

The radio link consists of frequency-modulated transmitter and receiver (Models 1584, Fred M. Link Co.). These are operated at approximately 70 mc, with deviation ± 75 kc full modulation, audio-frequency range 5,000 to 50,000 c, r-f output power 20 w. The transmitter uses the Armstrong system for the frequency modulation.

3. Receiving-station equipment.
   a. The 14 local oscillators are similar to the 14 airborne subcarrier ones. The 14 crystal filters were manufactured by Western Electric Company. Their mid-band frequency is at 92 kc. The attenuation distortion over a 200-c pass band is within ± 0.25 db. The suppression of all channels lying over 2,000 c either side of center frequency is over 50 db. The output of the crystal filters is amplified, rectified, and fed to mechanical recording galvanometers.
   b. The approximate weight and size of the frequency selector, exclusive of recording galvanometers, radio receiver, and power supply, are 600 lb and 17.5 cu ft for an experimental unit constructed without serious attention to weight.
   c. B power required for the frequency selector is 850 ma at 250 v direct current. Heater power is 28 amp at 6.3 v alternating current. Radio-receiver power is 2.2 amp at 24 v direct current. The total power, excluding the needs of the recording galvanometer, is about 750 w.

Pertinent data concerning the television equipment associated with this system can be summarized as follows:

1. Model No. 1. S.D.T.E.: Manufacturer — Farnsworth Television and Radio Corporation.

[e] In a private communication from Curtiss-Wright, it was pointed out that these frequencies give 1,288 troublesome third-order terms of the type $f_1 \pm f_2 \pm f_3$ and a few others. It was further stated that a new selection of frequencies had been found that would reduce the 1,288 to approximately 360. It is probably possible to find a set of frequencies which would do even better. The new kilocycle frequencies suggested are 6, 8, 10, 14.6, 17.2, 19.8, 26.4, 30.4, 35.0, 37.6, 41.6, 44.2, 46.8, 48.8.

2. Weight: camera, pressure chamber, and radio transmitter — 141 lb; power supply — 25 lb; cables — 2 lb; instrument panel, including six typical instruments and galvanometer block —108 lb; total — 276 lb.

3. Volume: camera, pressure chamber, and radio transmitter — 5.57 cu ft; power supply — 0.58 cu ft; instrument panel — 3.18 cu ft; total — 9.33 cu ft.

4. Power consumption: television apparatus — 33 amp at 22 v; lighting for instrument panel — 24 amp at 22 v; total — 57 amp at 22 v. (The 22 v are regulated down from the 28-v airplane power supply.)

5. Receiver: make — RCA; model — aircraft-type CRV-46ABP; volume — 1.42 cu ft; weight — 40 lb; power consumption — 8.9 amp at 25 v.

Naval Aircraft Experimental Station, Navy Yard, Philadelphia, Pennsylvania. This system consists of amplitude-modulated subcarriers for channels requiring frequency response up to 100 c, a mechanical commutator and a television unit. The subcarrier system, including television, has undergone a number of flights, with remote control, in the F4U airplane. Early models of this equipment were manufactured by the Raymond Rosen and Company, Philadelphia, Pennsylvania. Specifications for a newly engineered model have been completed.

The subcarrier system is a six-channel unit of the filter type. (See *Ordinary Subcarrier System*, under Section 1.6.1.) The subcarrier frequencies are, 3,000; 8,000; 15,000; 25,000; 29,000; and 49,000 c. These were selected to reduce the effects of cross modulation brought in by the radio link.

Pertinent data concerning the subcarrier system are as follows:

1. Airborne apparatus.
   a. The six bridges are fed from the six subcarrier oscillators through transformers. The outputs of the bridges are mixed through buffer amplifiers with a common plate resistance and are then fed to the transmitter through a master amplifier.
   b. The number of tubes per channel is two, exclusive of mixer, master amplifier, and transmitter.
   c. The approximate weight and volume of the airborne equipment, exclusive of the power supply and radio transmitter, are 39 lb and 0.6 cu ft.
   d. The B power, exclusive of the needs of the radio transmitter, is 40 ma at 250 v and 40 ma at 150 v, electronically regulated from a 350-v genemotor. The overall power requirement, including that for the radio transmitter, is 19 amp at 28 v direct current.
2. Radio link.

   The radio link consists of a Fred M. Link Co. frequency-modulated transmitter using the Armstrong system, and receiver, both Models No. 1584. These are operated at approximately 70 mc, with deviation ±75 kc full modulation, audio-frequency range 5,000 to 50,000 c, r-f output power 20 w.
3. Receiving-station apparatus.
   a. The filters are of the LC type. The response over a ±200-c pass band is flat to within 0.25 db. The suppression of frequencies either side of center is 10 db for 500 c, 40 db or more for 2,000 c. The output of the filters is amplified, rectified, and fed to mechanical recording galvanometers.
   b. The approximate weight and volume of the frequency selector, exclusive of recording galvanometers and radio receiver, is 65 lb and 2 cu ft.
   c. B power, exclusive of the needs of the radio receiver and recording galvanometers, is 30 ma at 250 v direct current and 20 ma at 150 v. The overall power requirement, including the needs of radio receiver, is 6 amp at 28 v direct current.

For use in connection with its subcarrier system the Naval Aircraft Experimental Station has a 50-channel commutator system which was designed and supplied by Baldwin-Southwark for the Navy and manufactured by Raymond Rosen Company. The pertinent data for the commutator system are as follows:

1. Airborne apparatus.
   a. The 50 bridges of the commutator unit are fed from a 6-v Edison storage battery. The output of each bridge is sampled ten times per second by means of a wiping-contact mechanical commutator connected at the output of each bridge

and driven by an approximately constant-speed direct-current motor. The direct-current pulses from the commutator are amplified and then used to modulate the 49-kc output of an oscillator. The modulated pulses are amplified and used to modulate the f-m transmitter. A 51st bridge having a fixed unbalance and a contact duration of twice that for the other bridges is used for identification and checking gains. This equipment was designed for use in place of the sixth channel of the Naval Aircraft Experimental Station Subcarrier System.

b. The number of tubes for oscillator and amplifiers is five.

c. The approximate volume of the airborne commutator modulator unit, exclusive of that of the Edison battery and power supply, is 1.65 cu ft.

d. The approximate weight of the airborne equipment, exclusive of that of power supplies and transmitter, is 60 lb.

e. The power for the bridge circuits is 1.2 amp at 6 v direct current. The power for the commutator motor and modulator is 6 amp at 28 v direct current. The overall power requirement, including the needs of the radio transmitter, is 12 amp at 28 v direct current.

2. Radio link.

The radio link is the same as that for the Naval Aircraft Experimental Station [NAES] system.

3. Receiving-station apparatus.

a. A filter rejects all but the 49-kc signals. The output of the filter is amplified, rectified and further amplified. The signal is applied to the y axis of a 5-in. cathode-ray oscilloscope and to a recording oscillograph which has a high-frequency galvanometer. The record produced consists of one double-width pulse of fixed amplitude followed by 50 single-width pulses of varying amplitude.

There is no report available as to the performance, reliability, servicing, etc., of the commutator system.

There have been no reports issued on the NAES television system. This is a special type of equipment characterized by compact design, light weight, and simplicity of operation. It incorporates some of the most advanced engineering features known to the television art at this time. For simplicity, the equipment does not conform to the commercial standards established for television as to number of lines, frame frequency, or scanning method. Optically, the sensitivity of the camera is about the same as for regular commercial equipment. In picture quality, the special compact equipment suffers slightly as compared to commercial broadcasting equipment. However, the quality obtained is adequate for applications where fine half-tone shading or gradation is not important, as, for example, in transmitting images of aircraft instrument panels.

The characteristics of the television equipment used by the NAES in structural flight tests are as follows:

1. Manufacturer: RCA-Victor Compact Television or Block Equipment, identified by RCA Drawings Nos. M121980, M121098, M120198, and M121598.

2. Weight: camera — 12 lb; camera control — 15 lb; radio transmitter — 11 lb; power supply — 31 lb; cables — 15 lb; instrument panel — 40 lb, including six typical instruments; total — 124 lb.

3. Volume: camera — 0.46 cu ft; camera control — 0.50 cu ft; radio transmitter — 0.48 cu ft; power supply — 0.47 cu ft; instrument panel — 3.15 cu ft; space front of panel and camera lens — 3.74 cu ft; total — 8.80 cu ft.

4. Power consumption of airborne equipment: television apparatus — 22 amp at 28 v; lighting for instrument panel — 10 amp at 28 v; total — 32 amp at 28 v.

5. Receiver: make — RCA-Victor; model — Modified Block III or ARJ Receiver; volume — 1.87 cu ft; weight — 54.5 lb; power consumption — 10 amp at 28 v.

C. G. Conn, Ltd., Elkhart, Indiana. The Conn system is a subcarrier type which uses the wattmeter principle for frequency selection. This work was done under NDRC contract and was discontinued before flight testing. Reports covering this work are OSRD Nos. 1945 and 3426.

In the airborne equipment a phonic wheel generator driven by a 28-v d-c motor produces

14 subcarrier frequencies from 5,000 to 13,500 in steps of 500 c. The bridges are driven by power which comes from the phonic generator through transformers. The outputs of the bridges are coupled through buffer amplifiers with a common plate resistance and are fed through a master amplifier to the radio transmitter. In addition to the phonic wheel generator, only one tube per channel is required. For large numbers of channels this type of subcarrier frequency generation would be economical of space, power, and weight, provided the frequencies could be reliably stabilized. Also, the ratios of all subcarrier frequencies are invariant.

In the receiving equipment the wattmeter principle of frequency selection is used. The local oscillators consist of a phonic wheel driven by a synchronous motor fed by a 500-c signal from the transmitter phonic wheel. Considerable difficulty was experienced in keeping the synchronous motor from hunting which introduces a varying phase angle. This is serious because the wattmeter type of response depends upon the cosine of the phase angle between the locally generated frequency and the subcarrier frequency received from the airplane. Since it is assumed that the locally generated frequencies are synchronized with the airborne frequencies, some drifting of subcarrier frequencies is permitted. (See Section 1.6.1.) The wattmeter principle is applied through a square-law type of balance vacuum-tube circuit and a low-pass filter for each channel. Inasmuch as the wattmeter method is phase sensitive, the bridges can be operated on balance with subsequent economy of modulation range. (See Section 1.6.1.) It is quite possible that the wattmeter frequency selector could be made to work satisfactorily through the use of electronic generation of the local frequencies. Synchronization could be maintained through an unmodulated subcarrier, but *constant* phase relations must be insured. If suitable band-pass filters are available for the frequency selector, the wattmeter system as a whole is probably no better than the filter system and is somewhat more critical. However, this system does not have the advantage of phase sensitivity and of locking the frequency selector with the transmitted frequencies.

Rudolph Wurlitzer Company, North Tonawanda, New York. The Rudolph Wurlitzer Company has worked on two types of telemetering systems under NDRC contract. The first of these was *a pulse-modulation subcarrier system for*

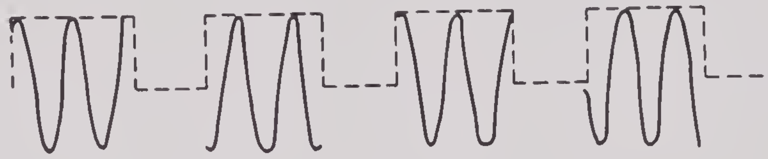

FIGURE 15. Modulation envelope.

telemetering of slowly varying aircraft flight instruments[1] (e.g., altimeter and compass); the second, *a system of subcarrier telemetering for channels carrying frequencies up to 300 c.*

The pertinent data for the first system are as follows:

1. Airborne apparatus.
   a. For each channel, a Pioneer Magnesyn-Autosyn torque amplifier is connected to

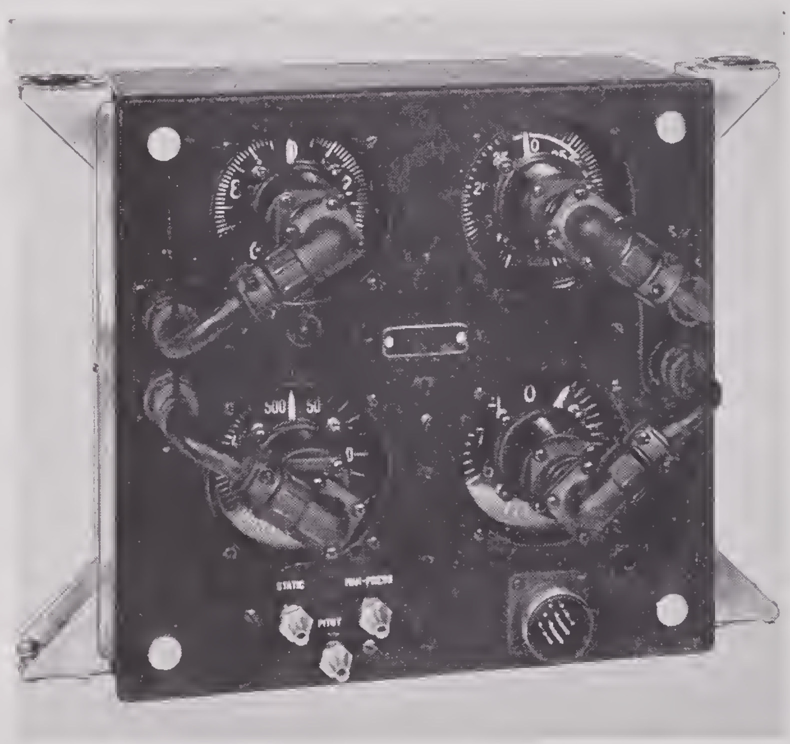

FIGURE 16. Transmitting instruments for Wurlitzer instrument-telemetering system.

the pointer of each instrument to be telemetered, as shown in Figure 16. The output of each torque amplifier drives a potentiometer, shown in Figure 17, which is arranged to vary the length of rectangular pulses recurring ten times a second. The complete transmitting equipment is shown in Figure 18. In Figure 15 these pulses are represented by the rec-

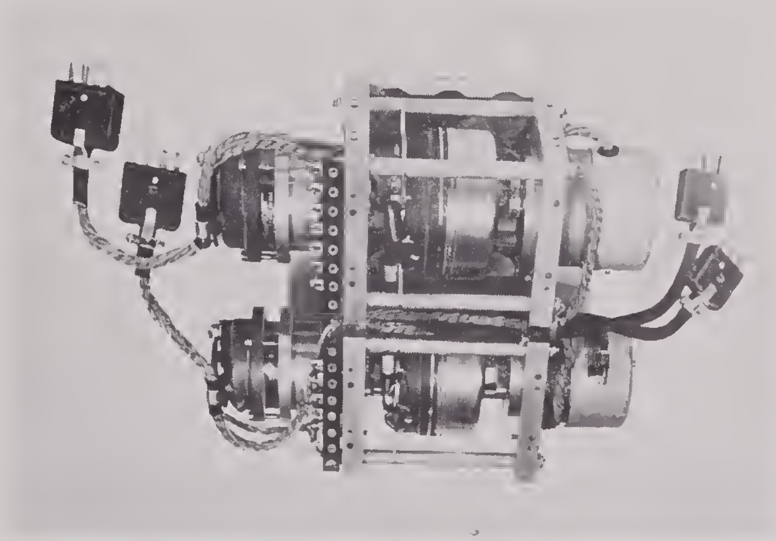

FIGURE 17. Precision potentiometer, Autosyn low-inertia motor assembly for Wurlitzer instrument-telemetering system.

tangular envelope. A subcarrier frequency is assigned to each channel and is turned on and off by an electronic valve controlled by the rectangular pulses. The subcarrier frequencies of one model are 9.5, 15, 27, 33, and 39 kc. The subcarrier output of a given channel appears in Figure 15. The length of the pulses depends upon the instrument reading, so that the result is essentially an amplitude-modulated subcarrier system.

b. The transmitter is an f-m Doolittle GFY-2.

2. Receiving apparatus.
   a. The receiver is an f-m Doolittle GVY-4.
   b. The frequency selector employs two resonant-coupled circuits as filters. The rectangular-wave-modulated subcarriers are fed to an electronic switch in each channel which is on when the pulse in that channel is on, and off when the pulse is off. When the electronic switch is on, it feeds a regulated current through a meter which has a long period compared to the rectangular-wave period. The meter thus reads an average which depends directly upon the duration of the rectangular pulses and, therefore, its reading corresponds to that of the instrument at the airborne end of the same

FIGURE 18. Complete transmitting equipment for Wurlitzer instrument-telemetering system.

FIGURE 19. Receiving instruments for Wurlitzer instrument-telemetering system.

channel. The meters are 270-degree milliammeters with the dial of each calibrated to match that of the corresponding aircraft instrument. This method gives a very high signal-to-noise ratio. By the sampling rule stated in Section 1.6.1, the maximum frequency response of the system should be the recurrence frequency of the rectangular pulses divided by 2 or 5 c. This equipment was flight-tested by the Aircraft Radio Laboratory at Wright Field.[24]

Flight tests at the Naval Aircraft Field in Philadelphia were held from July through August 1942.[12] The instrument showed drift difficulties, thereby requiring frequent calibration. The operation of the apparatus was not independent of input voltage, temperature, etc. The satisfactory range of the radio link was about 20 miles. Some, if not all, of these difficulties could certainly have been eliminated. However, for flight-instrument telemetering, it seemed more advisable to use television, which in the mean-

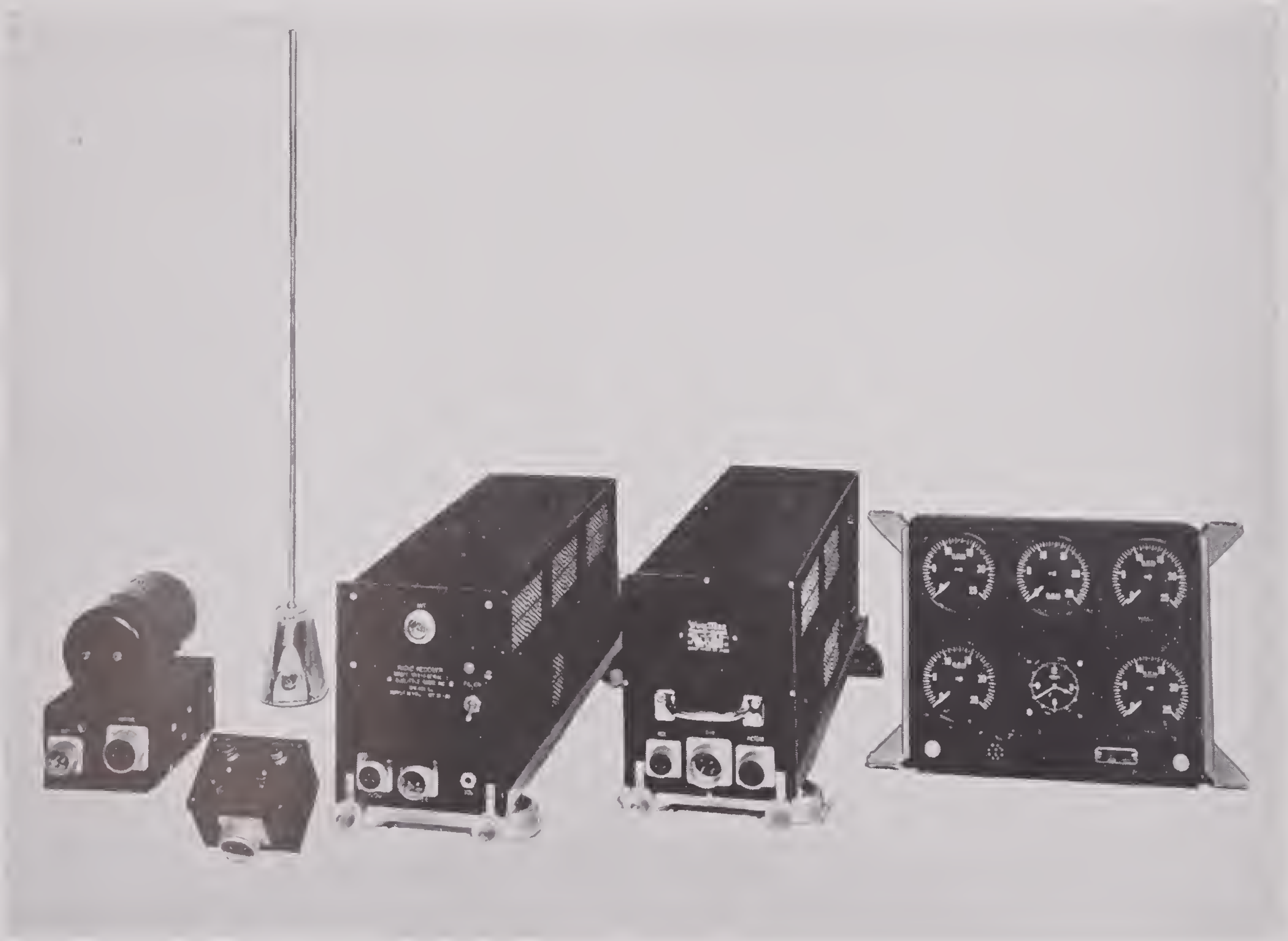

FIGURE 20. Complete receiving equipment for Wurlitzer instrument-telemetering system.

time had been developed to the point where it could be applied (Block III). One obvious advantage of television is that no mechanical connections to the flight instruments are required. Considering all these factors, work on this system was dropped.

In July 1943, the Wurlitzer Company commenced work on the second system, i.e., subcarrier telemetering for channels carrying frequencies up to 300 c. This work did not progress beyond the preliminary stage.[13] Four methods were proposed:

1. A subcarrier system of the filter type (Section 1.6.1) with a provision for varying the gain of the receiving-amplifier circuits by means of a monitoring signal carried in an additional channel. This would make up for changes in gain, etc., in the common parts of the circuits and radio link. Work on this plan was discontinued while other possibilities were being investigated.

2. A system which phase modulates the intelligence channels and at the receiver compares these phases with a monitoring signal transmitted over an additional channel. This appears to be desirable for instrument telemetering similar to that described in the above paragraphs, in which the phase shift is obtained by use of transformers and a potentiometer coupled by selsyns. It is not well suited, however, for use with strain-gauge bridges because of the difficulty in obtaining a sufficiently linear phase shift with change of gauge signal. No proposal was made for discrimination at the receiving end. It was suggested, however, that if the phase-shifting frequency were sufficiently low (as would be the case in instrument telemetering) the carrier frequency could possibly be used as a bridge subcarrier and also for strain-gauge indications. This would mean that instruments could be telemetered over a link already loaded with strain-gauge carriers.

3. A system employing subcarriers which would be modulated by a lower-frequency strain-gauge bridge carrier (2,000 c). Such a channel was built, but it was found that the frequency band required to handle the 2,000-c bridge carrier was too great to be used with the required number of channels and frequency pass of the radio link. That is, the outer side bands of the frequency-modulated signal extended into adjacent channels.

4. An amplitude-modulated subcarrier system with an amplitude stabilizer on all transmitter and receiving channels. The stabilizer was so arranged as to limit peak modulation to constant value, without introducing harmonics, in such a way as to give amplitude modulation inward as in Figure 21. The peak modulation value

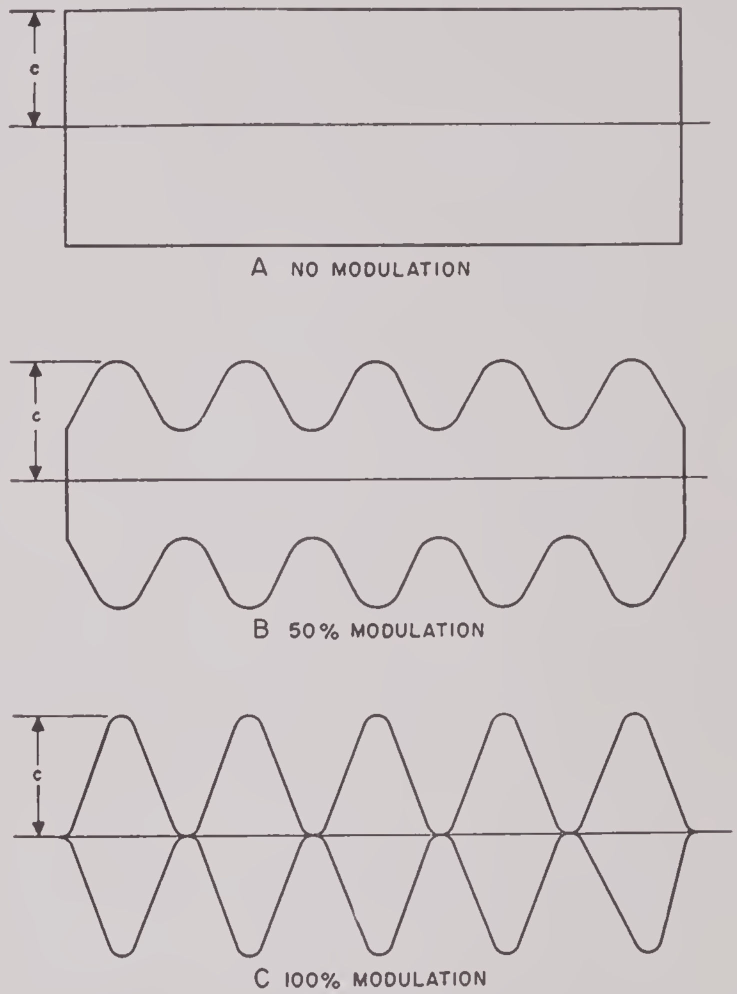

FIGURE 21. Wurlitzer modulation pattern, r-f.

was accurately stabilized by the use of a voltage-regulator tube and would, if working properly, compensate for changes in gain between the transmitter stabilizer and the receiver stabilizer. Work on this system was carried far enough to show that it was apparently feasible.

In all this work the Wurlitzer Company proposed driving the bridges at a lower frequency (2,000 c was tried) and modulating higher-frequency subcarriers with the outputs of the bridges. For amplitude modulation this requires a band width of at least 4,000 c; and for frequency modulation, a band width somewhat greater. The Wurlitzer contracts were terminated before further work was accomplished.

Boeing Aircraft Company, Seattle, Washington. As of September 1945, the Boeing Company had equipment in an advanced stage of construction which would be ready for tests in the near future. The design is a 20-channel amplitude-modulated subcarrier system flat within 0.2 db up to 150 c on the lower-frequency channels. Band width is greater on the higher-frequency channels and is sufficient to permit commutation with a pulse duration of 6 milliseconds. The system will normally be used with 14 channels for continuous recording of strains and vibrations up to 150 c, and 6 channels for transmission of 25 slowly varying signals by means of the combined subcarrier commutation system described later in this chapter.

Pertinent data concerning this system are as follows:

1. Airborne apparatus.
   a. Each of the 14 continuous channels consists of an oscillator, gauge balance circuit, and preamplifier mounted in a drawer assembly. These 14 drawers, and a 15th for a master amplifier, are housed in a box with a controlled fan for cooling and temperature regulation. The equipment for the 25 commutated channels is described later in this section.
   b. The oscillators are of the LC type with close compensation to minimize change of frequency or output voltage with temperature.
   c. The outputs of the oscillators are fed through balanced transformers to strain-gauge bridges or any other suitable type of gauge. Resistance and capacitance gauge balance controls are provided, and the resulting gauge signals are fed through midget step-up transformers to the preamplifier grids. The 14 preamplifier outputs are mixed in a two-stage master amplifier and fed from there to the radio transmitter.
   d. Two relays are mounted on each drawer for the purpose of automatically providing a zero point and a calibrating signal for each channel once each minute.
   e. The number of tubes per channel is three.
   f. The approximate weight and volume of the airborne equipment, exclusive of power supply and radio transmitter, are 75 lb and 1.6 cu ft. The total weight of the airborne equipment is 136 lb.
   g. B power, exclusive of that required for the radio transmitter, is 160 ma at 250 v, electronically regulated from a 375-v dynamotor. The heater consumption is 4.5 amp at 28 v and the total power requirement, including the radio transmitter, is 22 amp at 28 v.
2. Radio link.

   The radio link consists of a frequency-modulated transmitter and receiver, Models 1706T and 1706R of the Fred M. Link Co.
3. Receiving-station equipment.

   The range of subcarrier frequencies is 2,000 to 21,360 c. No effort to avoid harmonic frequencies is made, because it is practical to keep oscillator harmonics below 0.5 per cent, and harmonics generated in the transmission system are negligible when distortion is reduced to the extent necessary to minimize cross-modulation effects. Three-section LC filters are used, each one designed for a different frequency. Suppression at 150 c less than the next higher mid-band frequency is 45 db and at the adjacent mid-band frequency, 53 db. The filter output is rectified and fed to oscillograph galvanometers with 400-c resonant frequency.

   The weight of the apparatus is not known. The approximate volume of the frequency selector is 4.6 cu ft. B power required for the master amplifier and the rectifiers is 200 ma at 250 v. The overall power requirement, including that for the radio receiver, is 1.7 amp at 115 v alternating current. Exclusive of oscillographs and power supply, the receiving equipment occupies 38.5 in. of standard 19-in. rack. If the radio transmitter, the radio receiver, and the power supplies are excluded from consideration, the tube count is:

   Airborne: 3 per channel plus 2 for master amplifier;
   Receiver: 1 per channel plus 4 for master amplifier;
   Total (for 14 channels): 62.

Commutation Systems

The principles of commutation systems are not as generally known as are those of subcarrier systems, which have been used for many years by the telephone companies. In addition, their principles are somewhat more complicated in detail. For this reason considerably more space is devoted to outlines of the commutation systems in use and under development than to subcarrier systems.

Julien P. Friez and Sons, Division of Bendix Aviation Corporation, Baltimore, Maryland. The Friez method employs Radio-Sonde transmitting equipment designed for use in meteorological balloons. A description of this equipment is published in a Julien Friez manual.[31]

At the transmitting end a grid-blocking type oscillator is tuned for approximately 1 mc. To accomplish the blocking, the grid leak is shunted by a capacitor. The blocking oscillator is coupled into a 72.2-mc oscillator in such a way that the latter is on when the former is off, and vice versa. The 72.2-mc oscillator is coupled to an antenna. The blocking frequency depends upon the size of the grid-leak resistance and is varied from approximately 8 to 200 c. Intelligence in the channels is reduced to resistance variation and is inserted by a mechanical commutator into the grid circuit, thereby varying the blocking frequency. There are essentially four channels: one for pressure, one for humidity, and one each for high and low reference points. The commutator consists of an arm which wipes over a series of points through an arc of 30 degrees. The arm is activated by the mechanism of an aneroid barometer during the ascent. This aneroid switches in the four channels in order. One channel of points is connected to a fixed resistance which gives a "low reference point" every 5,000 ft of ascent and a "high reference point" every 15,000 ft of ascent. The temperature and humidity channels are suitably sandwiched between the reference points.

The transmitted signals are received by a special super-regenerative receiver. The audio-blocking frequencies, varying from 8 to 200 c, are fed to a frequency meter connected to a recorder which uses a carbon paper tape.

The blocking type of oscillator may prove to be of some convenience in other applications of telemetering (involving subcarriers) in which, for example, thermistors can be applied in the measurement of temperature, etc.

Consolidated Vultee Aircraft Corporation, San Diego, California. A description of the Vultee Radio Recorder has been published in the *Aeronautical Engineering Review*.[29] Several improvements have since been made, as described here.

In the airborne apparatus a motor-driven cam activates magnetically operated relays with contact points sealed in hydrogen, constructed by Electrical Research Products Company. All contact-point terminals are brought out to terminal boards where various combinations can be set up, such as sampling *one* channel *40* times a second and *40* other channels *once* each second, etc. Instrumentation is set up around resistance or reactance bridges. Each sample of each channel includes a number of cycles of the bridge frequency. The output of the commutator is rectified and fed into a variable oscillator having the frequency swing of 1,000 to 3,000 c. The frequency of the output is a function of the position or reading of the instrument. This is adjusted for constant amplitude and fed into the microphone line of a special f-m transmitter.

On the ground, the signals received are segregated by a special switching arrangement and each instrument record is plotted on its own individual chart. The charts are 6 in. wide, and $\frac{1}{16}$-in. linear movement represents one second of flight. Thus, each instrument has a continuous instantaneous plot of readings taken once per second.

Data on the airborne equipment are as follows: The dynamotor unit weighs 25 lb and has a volume of 0.5 cu ft; the scanning switch, 12 lb and 0.75 cu ft; the converter unit, 15 lb and 1 cu ft; the transmitter, 6 lb and 0.75 cu ft.

Princeton University, Princeton, New Jersey.[16-23] Pertinent data concerning telemetering developments at Princeton University under NDRC contract are as follows:

In the airborne apparatus the valves of Figure 8 are electronic and operate at a sampling rate F of 1,000 per second. The number of channels n is 20, giving $nF = 20{,}000$ per second. Each sampling sequence is initiated by a "master pulse"

scaled from switching pulses which operate the valves in sequence. These pulses are generated from the frequency used to drive strain-gauge bridges, accelerometers, etc. Three distinct methods of sampling have been developed.

1. Exemplified by Type I, Model B, illustrated in Figures 42 to 48 at end of chapter. The instruments, bridges, etc., are driven at 10 kc and are sampled during one-half of a period. Figure 22 illustrates this method of sampling. The sine wave in this figure is the output of a channel, e.g., a strain-gauge bridge. The samples of half-sine waves are taken an even number of half

Figure 22. Method of sampling in NDRC telemetering apparatus designated as Type I, Model B.

cycles apart. It is clear that such sampling essentially rectifies the output of the channel and, therefore, introduces d-c components which must be preserved by direct coupling throughout the radio link and other circuits. This requires the use of a reactance-tube-modulated radio link inasmuch as the Armstrong system cannot handle direct current. Direct coupling introduces the difficulty of drifts due to changes in the static characteristics of vacuum tubes and drifts in frequency of the radio link. The output of one

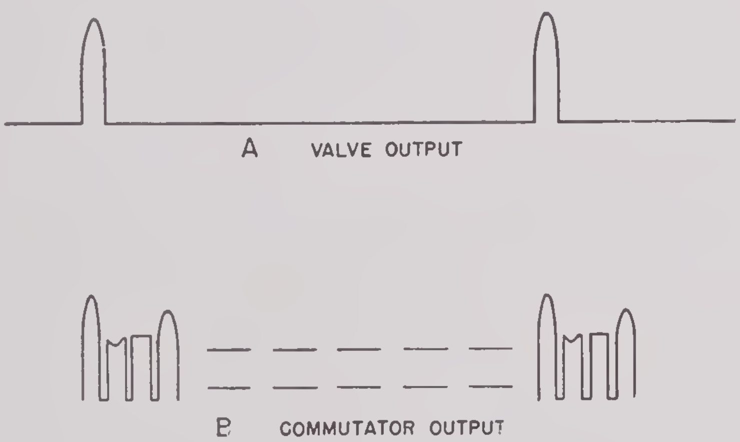

Figure 23. A, valve output; B, commutator output; Type I, Model B telemetering apparatus.

valve might appear as in Figure 23A, and the output of the commutator as in Figure 23B. The gaps between the channels are used for pulses to operate the receiver commutator.

2. Exemplified by Type II, Model A. The bridges are driven at 10 kc, but the outputs of the channels are sampled an odd number of half cycles apart to give up-and-down sampling as

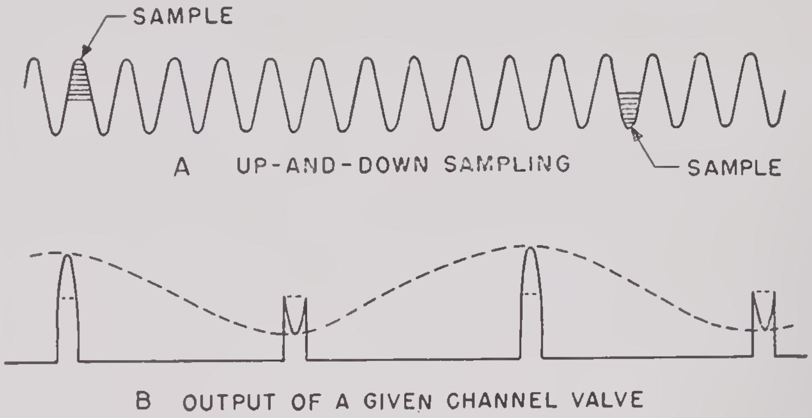

Figure 24. Sampling in NDRC telemetering apparatus designated as Type II, Model A.

in Figure 24A. (See Section under Bell Telephone Laboratories, New York, N. Y., in this chapter for application of a rotary-beam tube to commutation.) The output of a given channel valve appears as in Figure 24B.

If there were no signal in the channel, the output of each valve would be given by a dotted flat top. The introduction of the signal into the channel results in the up-and-down half-sine waves. The dashed sine wave is the lowest fre-

Figure 25. Commutator output; Type II, Model A, telemetering apparatus.

quency component introduced by the up-and-down half-sine waves and has a frequency of $F/2$, and an amplitude proportional to the output of the channel. Thus, the sampling does not introduce the d-c component as in Method 1. This eliminates the necessity for direct coupling and the dependence on the drift of the static characteristics of the tubes, on the frequency drift of the transmitter and receiver, etc. The output of the commutator appears as in Figure 25. The lowest component which the radio transmitter must handle is about 500 c less modulation frequency.

3. Exemplified by Type III, Model A. It uses 20 kc on the bridges and samples full sine waves, as shown in Figure 26. The output of the com-

mutator is somewhat as shown in Figure 27. This sampling does not introduce a d-c component. Ideally, the lowest frequency component will be the sampling rate $F = 1{,}000$ per second.

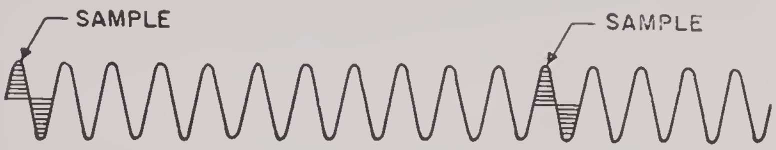

FIGURE 26. Sampling in NDRC telemetering apparatus designated as Type III, Model A.

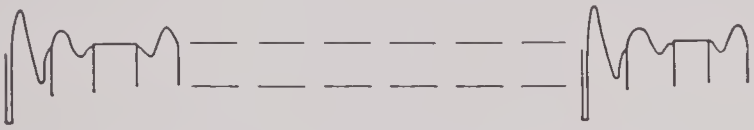

FIGURE 27. Output of commutator in NDRC telemetering apparatus designated as Type III, Model A.

The ground-receiver equipment can be summarized in the description of the following methods:

1. The radio transmission is by a frequency-modulated link which uses a reactance-tube modulator to preserve the d-c components. A pulse extractor connected to the output of the discriminator is used to extract switching pulses from the gaps between the channels (illustrated in Figure 23). The master pulse is transmitted by cutting off for an instant one of the multipliers in the transmitter, which cuts off its radiation. This creates a pulse in the grid of one of the limiters in the receiver. The switching pulses and master pulses so carried over the radio link are used to drive the receiver commutator. In this way it is positively locked in with the transmitter commutator and achieves synchronization in 1 millisecond. The output of each receiver valve (see Figure 9B) has the samples formed into a smooth signal and fed to recording galvanometers.

2. The radio link, pulse selector, etc., can be the same as in Method 1, except direct coupling is not used. The output of each receiver valve is fed through a low-pass filter to carry the 500-c component and cut off everything above. This component is then rectified and fed to the recording galvanometers. This system is not phase sensitive. (See Section 1.6.1.)

3. The sampling is designed to be used with a cathode-ray recording device. Each channel is provided with its own cathode-ray tube on which the complete signal, received from the discriminator, is spread out by a sweep generated from the master pulse which is carried in a manner analogous to the switching pulses in Methods 1 and 2. No switching pulses are required. Figure 28 shows the signal on a cathode-ray tube. A mask, which is opaque except for a slit, is put over the tube and the centering is adjusted to select the desired channel. The tube is then photographed on moving film, which moves more slowly than the sweep. The envelope of the samples recreates the envelope in the output of the channel before it was sampled. The intelligence is measured from tip to tip. This method is phase sensitive because the slope of the connecting lines is positive or negative depending upon whether, for example, a strain-gauge bridge is stretched or compressed. This method of sampling and recording is independent of

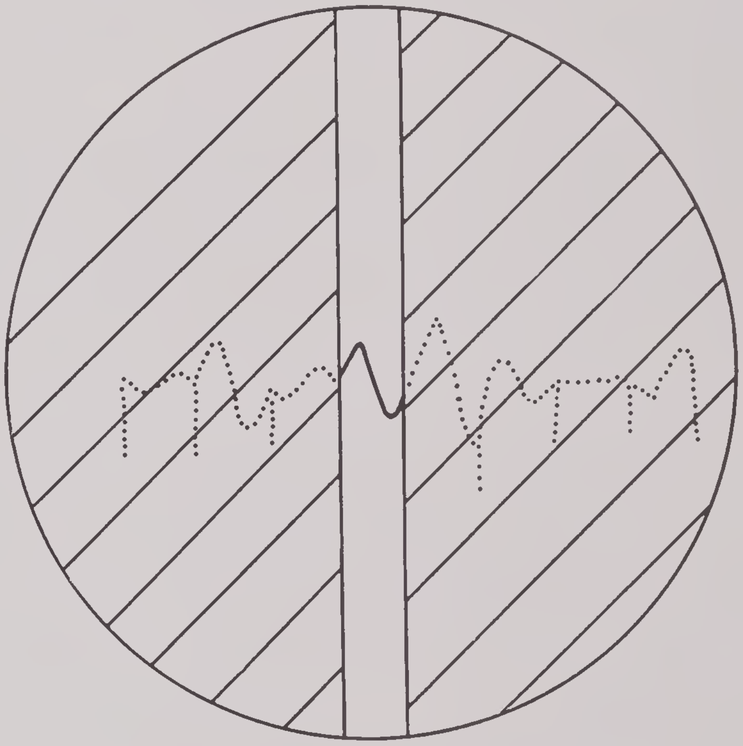

FIGURE 28. Signal from single channel chosen by mask over cathode-ray tube (NDRC telemetering apparatus designated as Type III, Model A).

drifts over periods of time longer than the period of bridge-driving frequency. In Model A, Type III, currently being developed, the cameras are so arranged as to photograph three channels together with timing, etc., on a 35-mm film. Six films are required to photograph 18 channels. The Armstrong system, which is crystal controlled, can be used in the radio link.

The airborne apparatus is essentially the same for the three methods except for differences in exciting frequencies and the scaling ratio between the master pulses. The receiving apparatus is different for the three systems. Table 2 gives a comparison of the receivers. The number of tubes stated does not include those in the radio receiver or in the voltage supplies and regulators.

Inasmuch as Method 1 requires no filters and was developed before the other methods, it was incorporated in prototype apparatus and flight tested[19] in the YP-59 jet-propelled aircraft at the Bell Aircraft Corporation at Niagara Falls. Automatic calibration provisions are being built into the airborne commutator to give zero and 10 calibration points on each channel in sequence. The complete operation will require about 15 seconds and can be initiated by a single pulse from the remote-control apparatus. Relays have been set up to calibrate before and after each maneuver, to give a complete check on the apparatus. This eliminates the difficulty of slow drift which is hard to remove entirely from the direct-coupled circuits and radio link.

The equipment used in the YP-59 is shown in Figures 29 to 31 inclusive. Its physical characteristics are as follows:

1. Airborne equipment.
   a. Eighteen channels — one channel used for zero level.
      (1) Instrumentation includes 13 strain-gauge bridges, two accelerometers, and one elevator position indicator.
      (2) Driving frequency of bridge, etc., 10 kc.
      (3) Sampling rate, 1,000 per second. Switching rate, 20,000 per second.
      (4) Average number of tubes per channel is four (exclusive of radio transmitter).
   b. Weight and volume components.

(1) Commutator amplifier unit	75 lb	2 cu ft
(2) Voltage regulator-filter	25 lb	0.5 cu ft
(3) Radio transmitter	15 lb	0.5 cu ft
(4) Two dynamotors	20 lb	...
(5) Total	135 lb	3 cu ft

   c. Power requirement.
      (1) B power, 400 ma at 250 v direct current, regulated from 450 v direct current.
      (2) Total power, 35 amp at 28 v direct current.

Table 2

Method	Number of tubes per channel	Total number of tubes	Frequency band required of radio link and associated circuits to keep cross talk down 50 db.	Drift due to frequency. Drift of radio link, shift in static characteristics of tubes, etc.	Recording instrument
1	5	107	0 - 70,000 c	Dependent except for frequency clamping circuit used to regulate frequency of local oscillator to keep constant output of an unmodulated channel.	Mechanical multi-channel oscillograph
2	6	125	400 - 70,000 c	Independent of slow drifts which are eliminated by coupling networks.	Mechanical multi-channel oscillograph
3	1 cathode-ray tube	16 tubes plus 18 cathode-ray tubes	1,000 - 70,000 c	Independent of drifts.	18 cathode-ray tubes photographed on six 35-mm films

2. Radio link.
   a. A frequency-modulated radio link developed at Princeton and constructed by Fred M. Link Co. is employed.
   b. The modulation is obtained by use of a reactance tube to give a frequency swing of ±125 kc with a deviation ratio of approximately 1.5. A carrier frequency of 69 mc is obtained by beating the reactance-modulated frequency of 3 mc against a crystal-controlled frequency of 72 mc. The r-f power output is about 30 w. A quarter-wave horizontal antenna is used. The standing-wave ratio on the feeder coaxial cable is about 2.
   c. The receiver uses two intermediate frequencies and a double limiter. The discriminator is arranged for a linear output with a maximum of 60 v peak to peak.
3. Ground equipment.
   a. The receiver commutator is synchronized with the transmitter commutator by means of pulses carried by the radio link. The samples are reassembled electrically and fed into a Consolidated recording galvanometer. Figure 33 is a typical record. The frequency band of each channel, exclusive of galvanometer, is flat from 0 to 200 c.
   b. Full modulation gives about 4 in. peak-to-peak deflection on the oscillograph.
   c. The average number of tubes per channel is six, exclusive of the radio receiver.
   d. The overall weight of the receiving apparatus is about 400 lb.
   e. The overall power requirement is 50 amp at 28 v direct current.

Bell Telephone Laboratories, New York, New York. The Bell Telephone Laboratories [BTL] have developed a magnetically rotated-beam tube, making possible the use of many grids and anodes for electronic commutation.[28,30] Features of the rotary-beam tube are its small size, low voltage, linear characteristics, and high-beam currents. A rotating magnetic field to drive the tube can be readily obtained by the use of

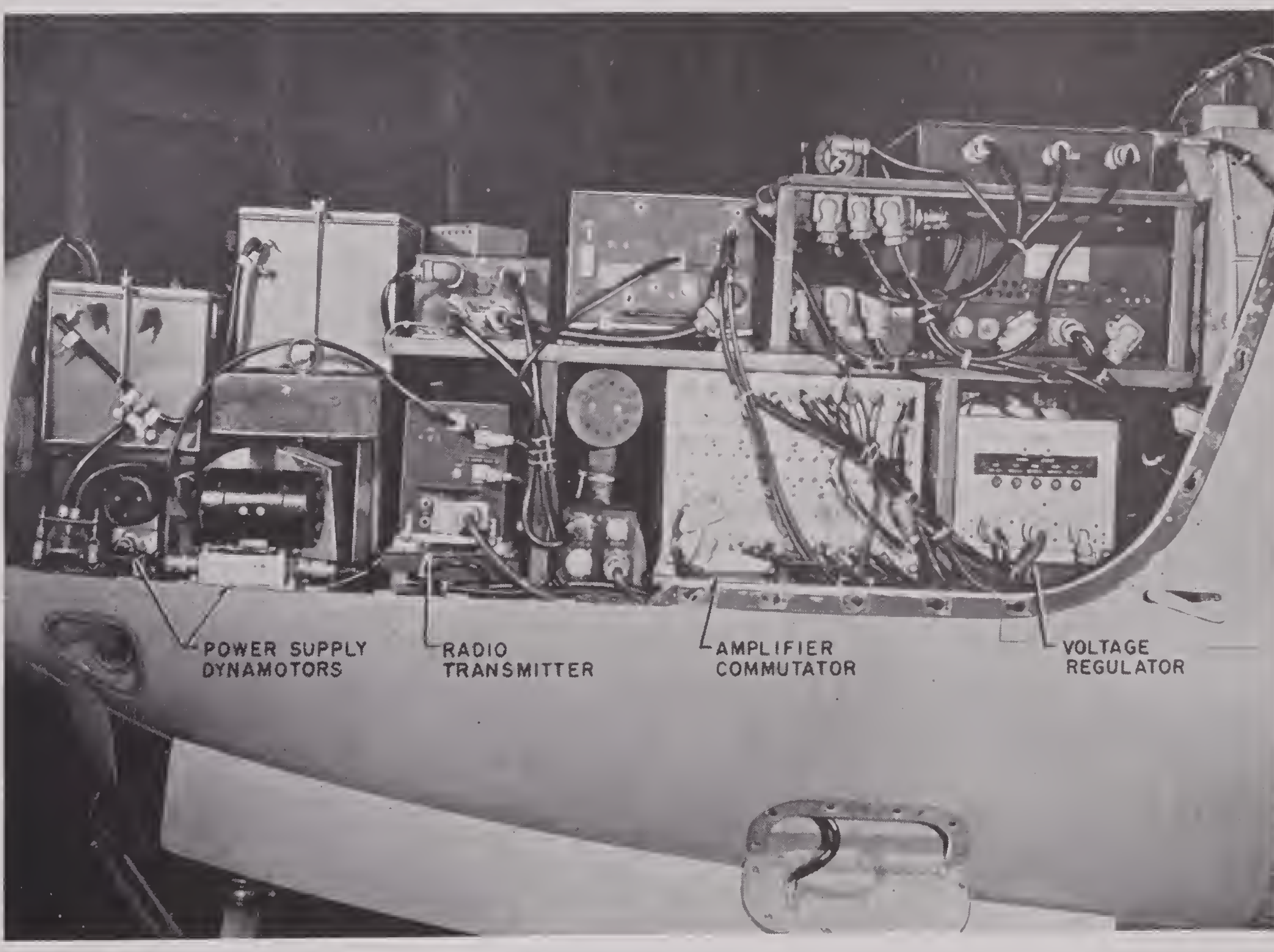

FIGURE 29. Front view of telemetering equipment in YP-59.

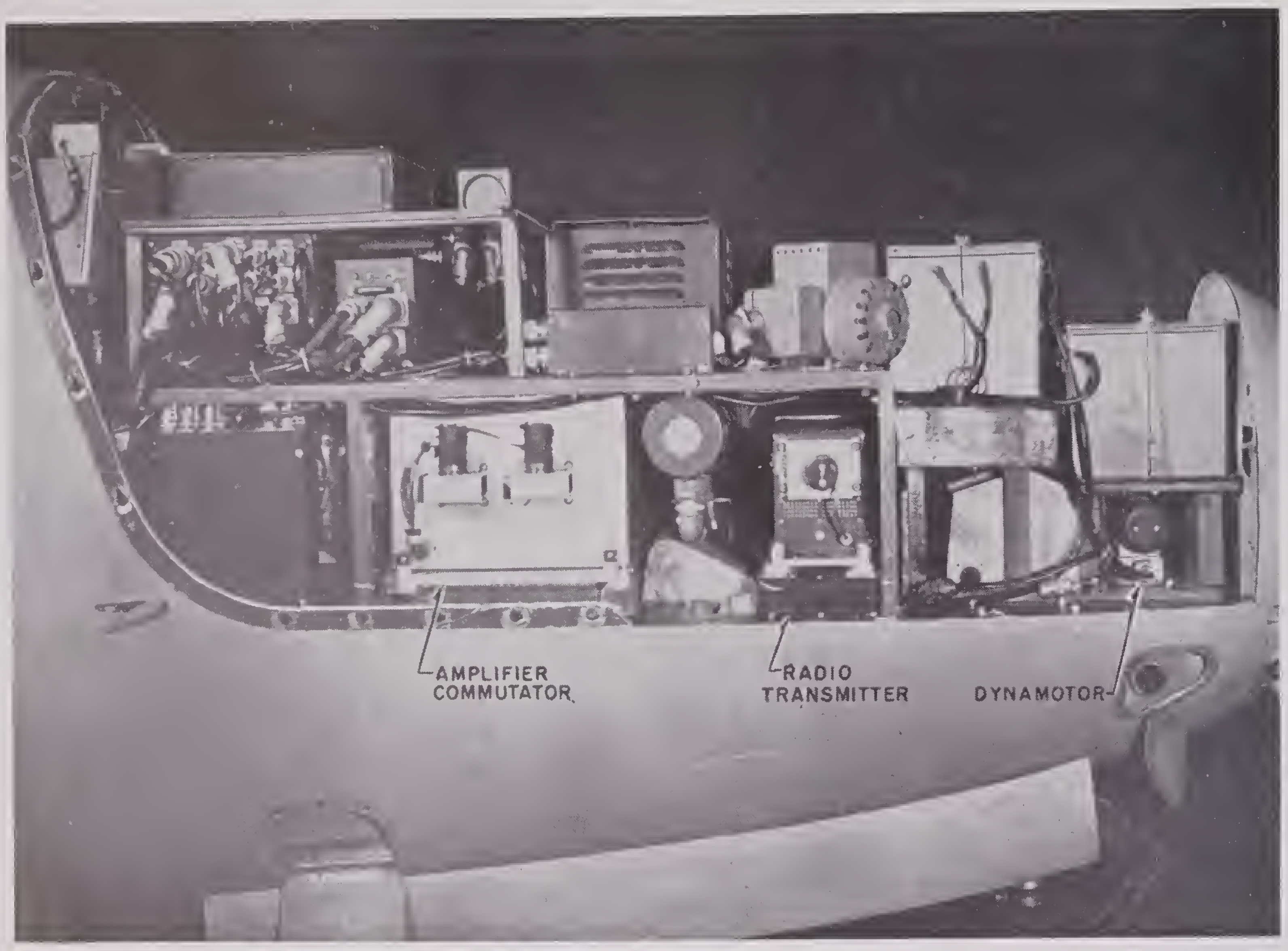

FIGURE 30. Rear view of telemetering equipment in YP-59.

the stator of a small polyphase alternating-current motor. Single-phase power can be split for this purpose. At low rotating frequencies the power loss is mostly in the copper of the windings, but at higher frequencies core loss becomes important. It should be possible to rotate the beam at 1,000 c using just a few watts.

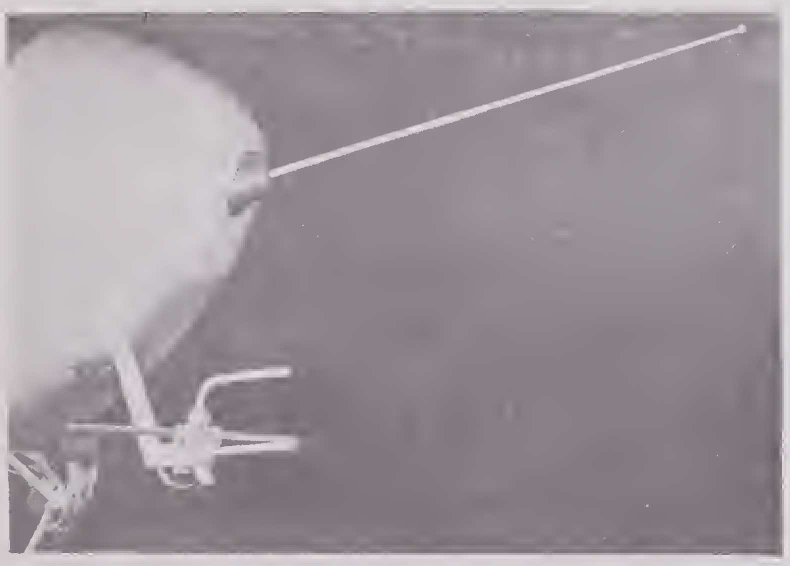

FIGURE 31. Telemetering antenna (long one).

The original papers[28,30] describe a 30-anode tube which could be used to commutate 30 channels. This tube, shown in Figure 32 is approximately 2¼ in. in diameter and 6 in. long. The tube has a single control grid surrounding the cathode and a suppressor grid in front of each anode. For the airborne commutator the anodes can all be connected together and the suppressor grids connected to each channel. These modulate the beam in succession, similar to the action of the Princeton commutator which uses standard receiving tubes. At the receiving station the rotating beam is synchronized with the airborne tube, and all suppressor grids are tied together. The modulation is applied to the grid surrounding the cathode and each anode forms a channel output.

This tube could be used very well with cathode-ray recording by Method 3 under the Princeton system, or with modifications of Method 2. It would probably be desirable to use one half of the rotating beam frequency to drive the instru-

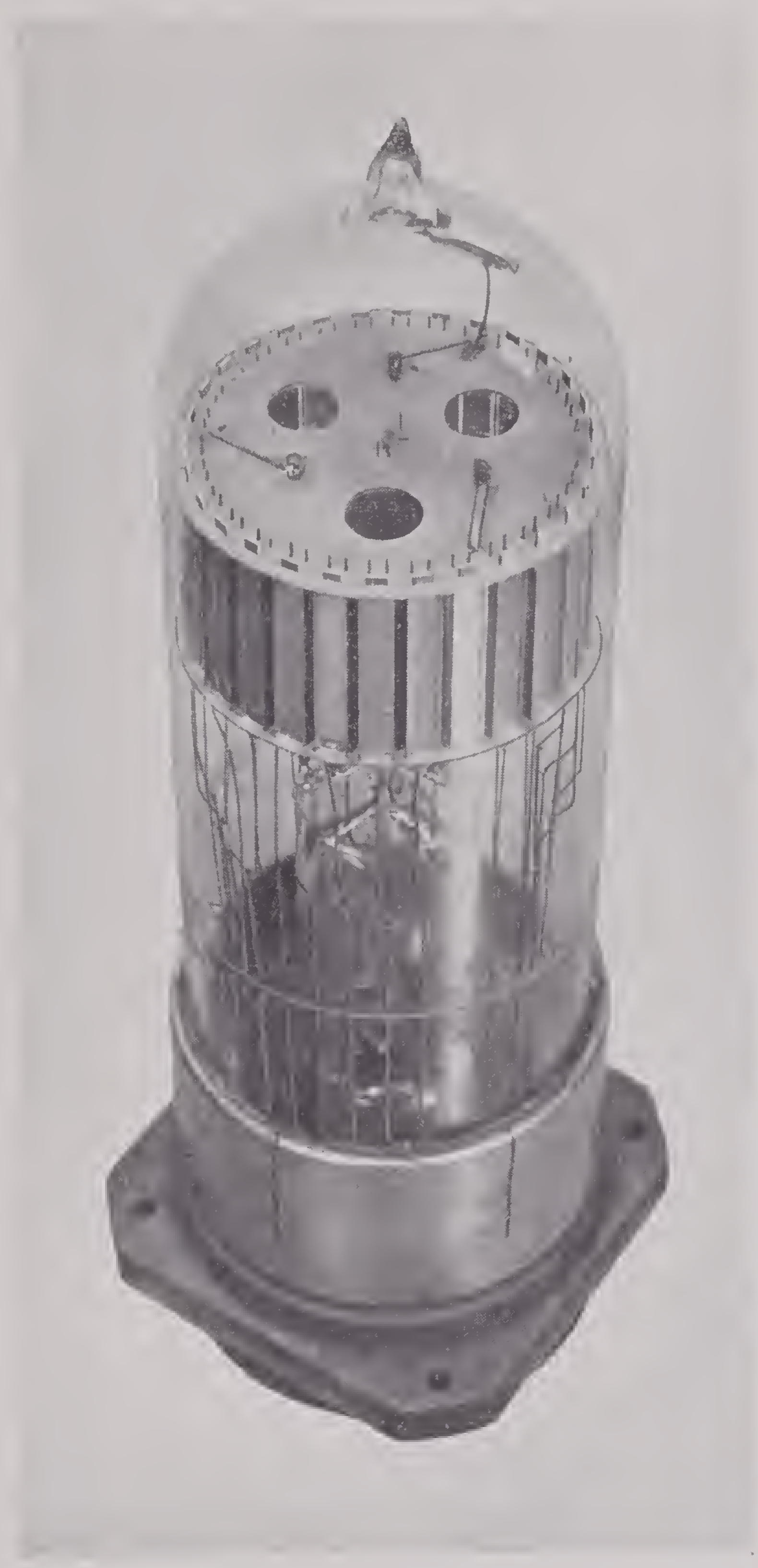

FIGURE 32. 30-anode magnetically rotated beam tube (top view).

mentation and to phase each channel so that the sampling takes place at the peaks of the sine waves in an up-and-down method. This requires minimum frequency response of the radio link, eliminates d-c components and permits low operating frequencies of the bridges, thus minimizing the effects of distributed capacitance, etc. The cathode-ray trace would appear somewhat as in Figure 28, with much flatter peaks.

The BTL have also developed a cathode-ray tube which has many anodes. These are divided by little stalls which make possible modulation by use of the secondary-electron characteristics of the anodes. An intensity grid modulating the cathode-ray beam is also provided. The tube is very compact and requires practically no power to sweep the beam. The plates can be arranged in a circle for rotary scanning or in rows for television-type scanning. This type of tube can be used in the same general way as the magnetically rotated beam tubes.

Both types of the tube initially produced at BTL were further developed under a subcontract with Princeton University to allow application to commutation telemetering. The system, known as Type II, Model B,[23] shows excellent possibilities for extreme compactness, more channels (about 30), low power consumption and small weight.

Combination Subcarrier-Commutation Systems

Boeing Aircraft Company, Seattle, Washington.[32] The pertinent data of this system are:

1. Airborne apparatus.
   a. The Boeing system makes use of an array of five oscillators and six commutator valves arranged as in Figure 14 to give 30 channels. One of the six channels on each oscillator is used to transmit a signal which controls the gain of an automatic volume control amplifier on the ground. Thus, 25 channels are available for transmission of intelligence. Provision is made for different types of gauges, including wire strain gauges, magnetic gauges and slide wires.
   b. The commutator is electronic and has a switching rate of 120 per second and a sampling rate of 20 per second. A sixth oscillator is amplitude-modulated at 120 c for transmission of switching and synchronizing signals to the ground. Automatic calibration is provided in each channel once each minute, and gives a zero input signal and one calibration voltage.
   c. The total number of tubes, exclusive of those in the transmitter and the power supply, is 59.
   d. The volume of the airborne equipment,

exclusive of power supply and the transmitter, is 4.4 cu ft. Its weight is 175 lb.

e. B power, exclusive of that required for the radio transmitter, is 200 ma at 250 v, electronically regulated. The overall power requirement, including that for the radio transmitter is 26 amp at 28 v direct current.

2. Radio link.

Fred M. Link Company Models 1584 are used with frequency-modulated transmitter and receiver.

3. Receiving apparatus.

a. The receiver output drives five amplifiers which feed five two-section LC filters. The gain of these amplifiers is regulated by the automatic volume control signals. These amplifiers are also used for blanking between pulses and for rounding the pulse tops to reduce the necessary filter band width.

b. Separation of channels is accomplished by a square array, essentially the same as in Figure 14, except that five filters replace the subcarrier generators while rectifiers and galvanometers replace the bridges. That is, the circuit works in reverse.

c. The electronic commutator is operated by pulses derived from the 120-c modulation on the sixth subcarrier. This subcarrier is blanked out in the transmitter during every switching interval in order to provide a master synchronizing pulse. In this way the transmitting and receiving commutators are automatically brought into step after any interruption of the radio signals.

d. The signal received by each galvanometer rectifier consists of 20 pulses or bursts of the subcarrier per second. Each pulse lasts about 6 msec.

e. The galvanometers are fast enough to follow the envelope of the individual pulses, so it is not necessary to use an integrating circuit. Low paper speed is used, and the record appears as a succession of dots. Calibrating signals are recorded automatically along with the gauge signals.

f. The total number of receiving tubes, exclusive of those in the radio receiver and the power supply, is 98. This number can be reduced to 68 if the automatic volume control, which is only a convenience, is removed.

g. The receiving equipment, exclusive of the radio receiver and the oscillographs, occupies 72 in. of 19-in. rack space.

h. The overall power consumption, including that of the radio receiver and the three oscillographs, is 15 amp at 115 v alternating current.

Discussion of Test Results

The subcarrier systems which have been described developed cross-modulation difficulty under certain conditions, as explained in the introduction to this report. Numerous modifications were made in placement of subcarrier frequencies in relation to one another and in development of appropriate band-pass filters to act as frequency selectors. Final results led to the conclusion that the development of a more linear radio link was essential. Accordingly, at the suggestion of the various groups concerned, the Navy Department early in 1945 issued a directive to NDRC (NA-226) for assistance in the development of an appropriate radio link. This link was to permit equipment already developed to be used to transmit indications by subcarriers. It is probable that such a link could have been developed and constructed, thereby eliminating some of the difficulties in subcarrier operation. However, work was terminated on this project with the cessation of hostilities.

Flight tests of the electronic-commutation apparatus Type I, Model B developed under NDRC, were carried out in the YP-59 jet-propelled aircraft and in a Curtiss Helldiver Type SB2C-3. The latter test was under the supervision of Princeton University personnel associated with Contract OEMsr-1037. Figure 33 shows a typical oscillograph record transmitted from a 3.5g pullout in the Helldiver. A number of channels, whose indications are represented by the heavy lines on the chart, were connected to strain-gauge bridges in the aircraft. The gauges were mounted on various wing spars which show stress under various conditions of maneuver of the aircraft. Two other channels were used to indicate air speed and acceleration

of the aircraft in directions parallel to and normal to its main axis. This particular set of records, at its start, shows flight conditions wherein the various stresses and accelerations are relatively constant, except for engine vibration which appears in the accelerometer channel to a considerable degree. These normal conditions are for flight in a relatively steep dive with the airspeed increasing slowly because the terminal velocity had almost been reached prior to the portion of the record shown. When the record is about 30 per cent completed, the pullout from this dive is begun with the associated decrease in airspeed, increase in some wing loadings and decrease in others, and a large increase in acceleration. The end of the chart shows the conditions on returning to level flight. The record adequately illustrates the application of telemetering to the transmission of strain and acceleration data from an aircraft to ground by a radio link.

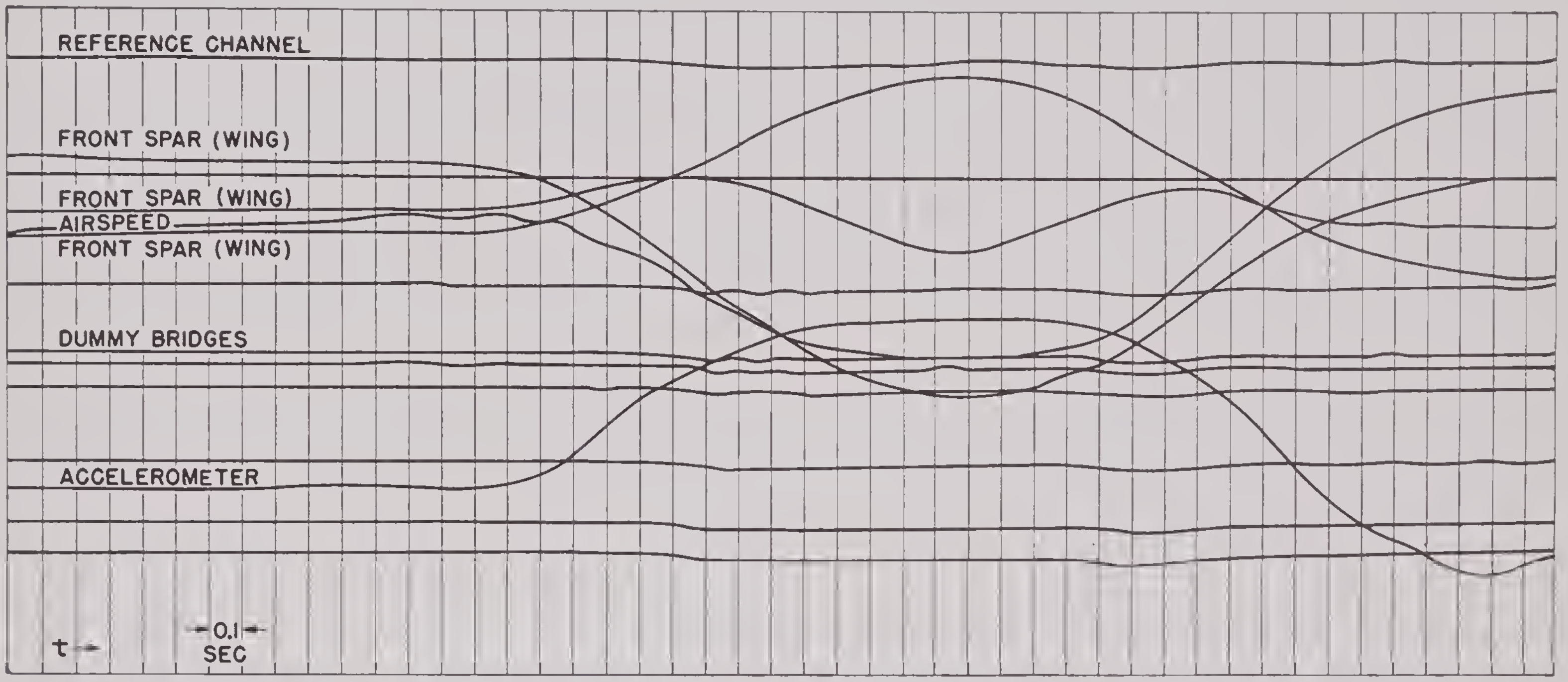

FIGURE 33. Sketch of oscillographic record of typical 3.5g pullout, transmitted from project test aircraft SB2C-3 by NDRC telemetering equipment Type I, Model B.

Results indicated that commutation telemetering in the form tested is satisfactory and will adapt itself to the addition of more channels by subcommutation or, where high-intelligence frequency response is desired, to the use of additional switching channels employing rotary-beam tubes with multiple targets. As a result of the various tests, preproduction prototypes of Type I, Model B, were manufactured by another contractor (Raymond Rosen and Company, OEMsr-1399) under the supervision of NDRC, to permit Service groups to obtain the apparatus needed for their applications. Pictures of this apparatus are given in Figures 42 to 48 inclusive, reproduced with the circuit diagrams in Section 1.7 of this report.

To illustrate the general features of this equipment, and installation details, circuit drawings are reproduced in Section 1.7.

The Type II, Model A, Type II, Model B, and Type III, Model A systems described in the body of this report were approaching the prototype production stage in October 1945, when NDRC transferred the contract with Princeton University to the Navy Department.

GUIDED-MISSILE TELEMETERING[28]

The telemetering developments which have been described are adaptable in various forms and combinations to the transmission of information from guided missiles. In the case of such vehicles, telemetering is essential, since there are no pilots to obtain any sort of performance data. Using the principles established in previous telemetering studies, work was started on the development of various combination systems for use in guided missiles under development by the Army and Navy. This work was under LARK directive NA-242. When the contract with Princeton University was transferred to the Navy Department, work was being continued under that contract on the development of such apparatus.

1.7 CIRCUIT DRAWINGS AND PICTURES — NDRC. TYPE I, MODEL B TELEMETERING EQUIPMENT

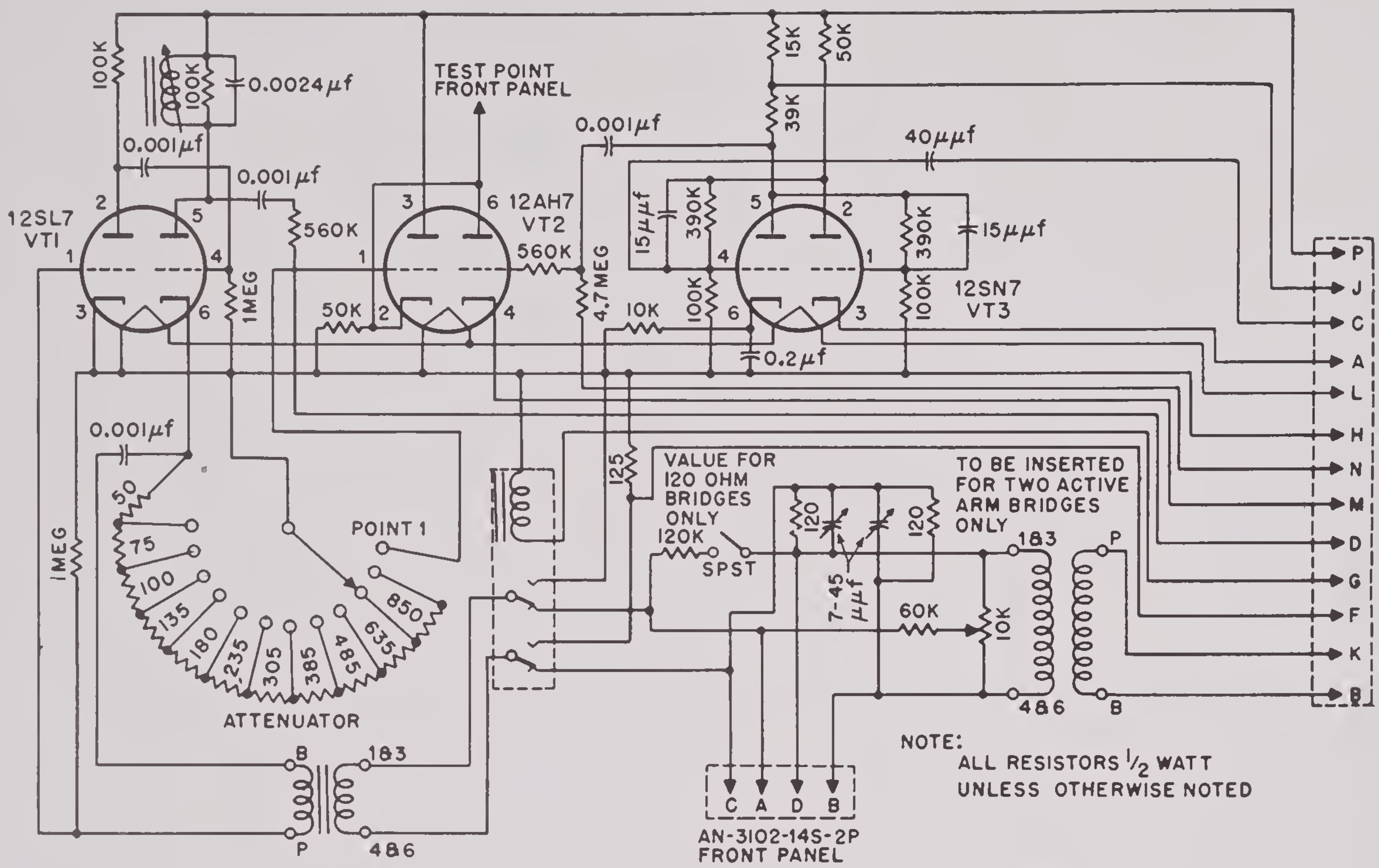

FIGURE 34. Transmitter strain-gauge channel (NDRC Type I, Model B).

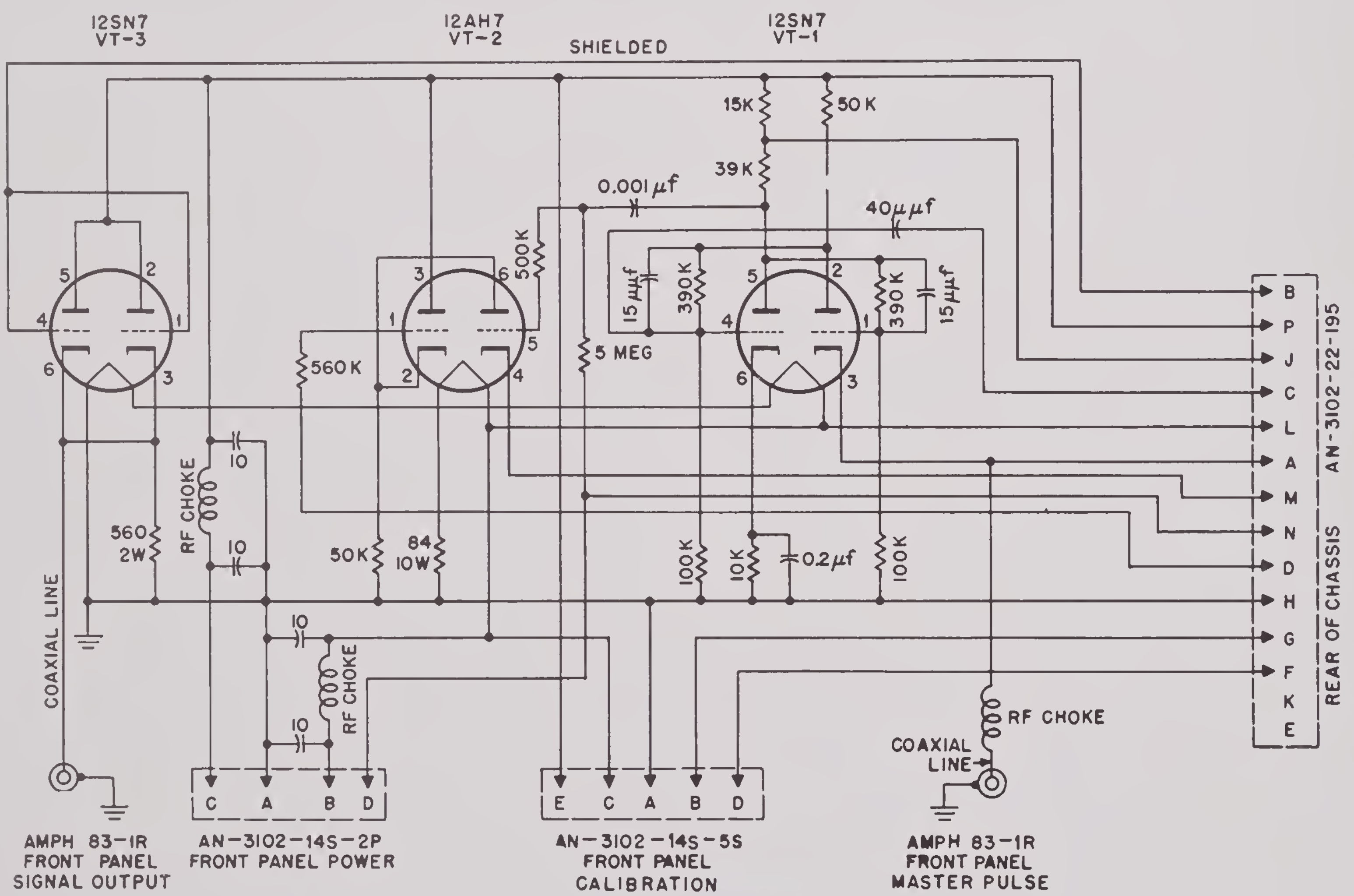

FIGURE 35. Transmitter channel No. 2 (NDRC Type I, Model B).

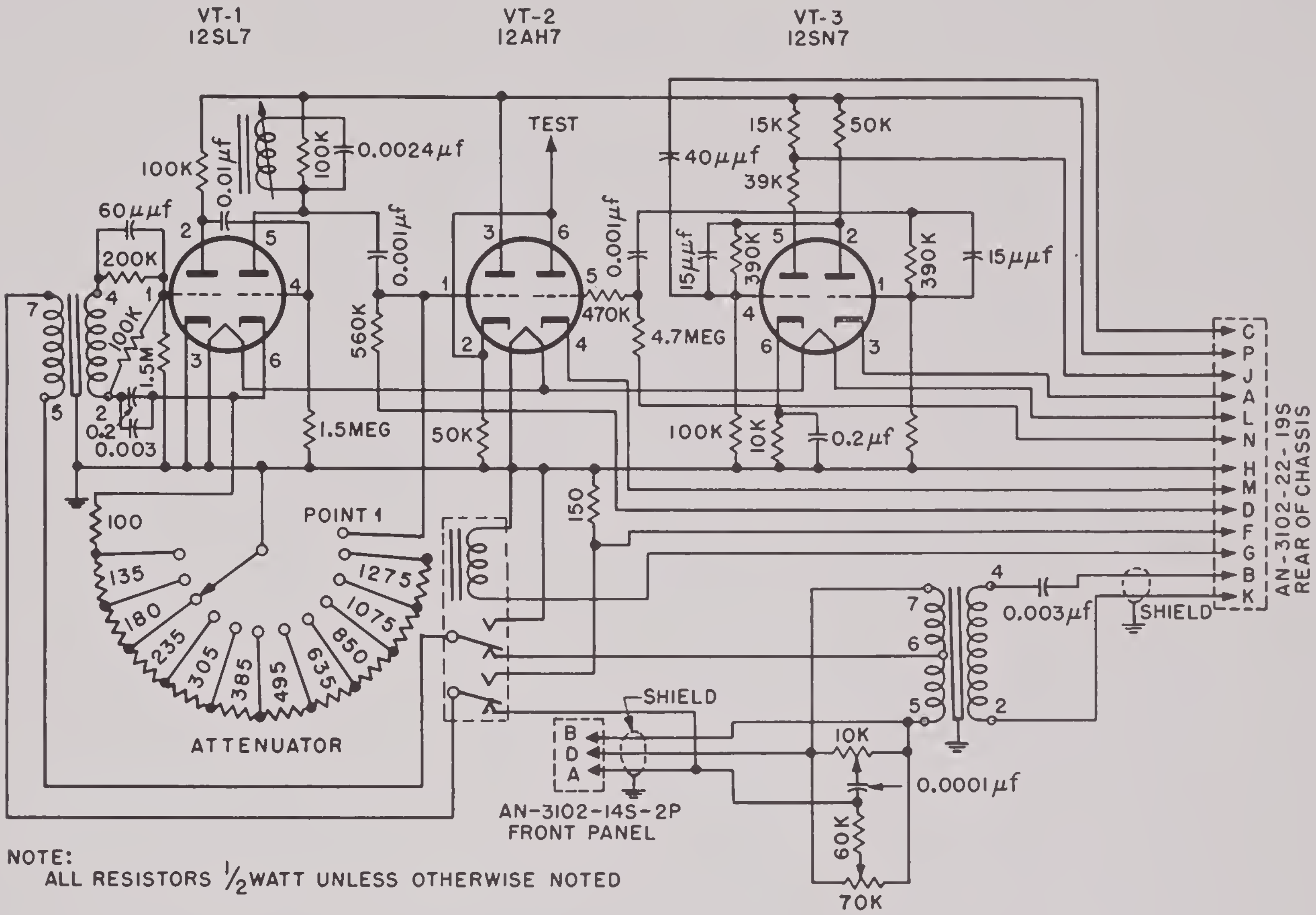

FIGURE 36. Transmitter accelerometer channel (NDRC Type I, Model B).

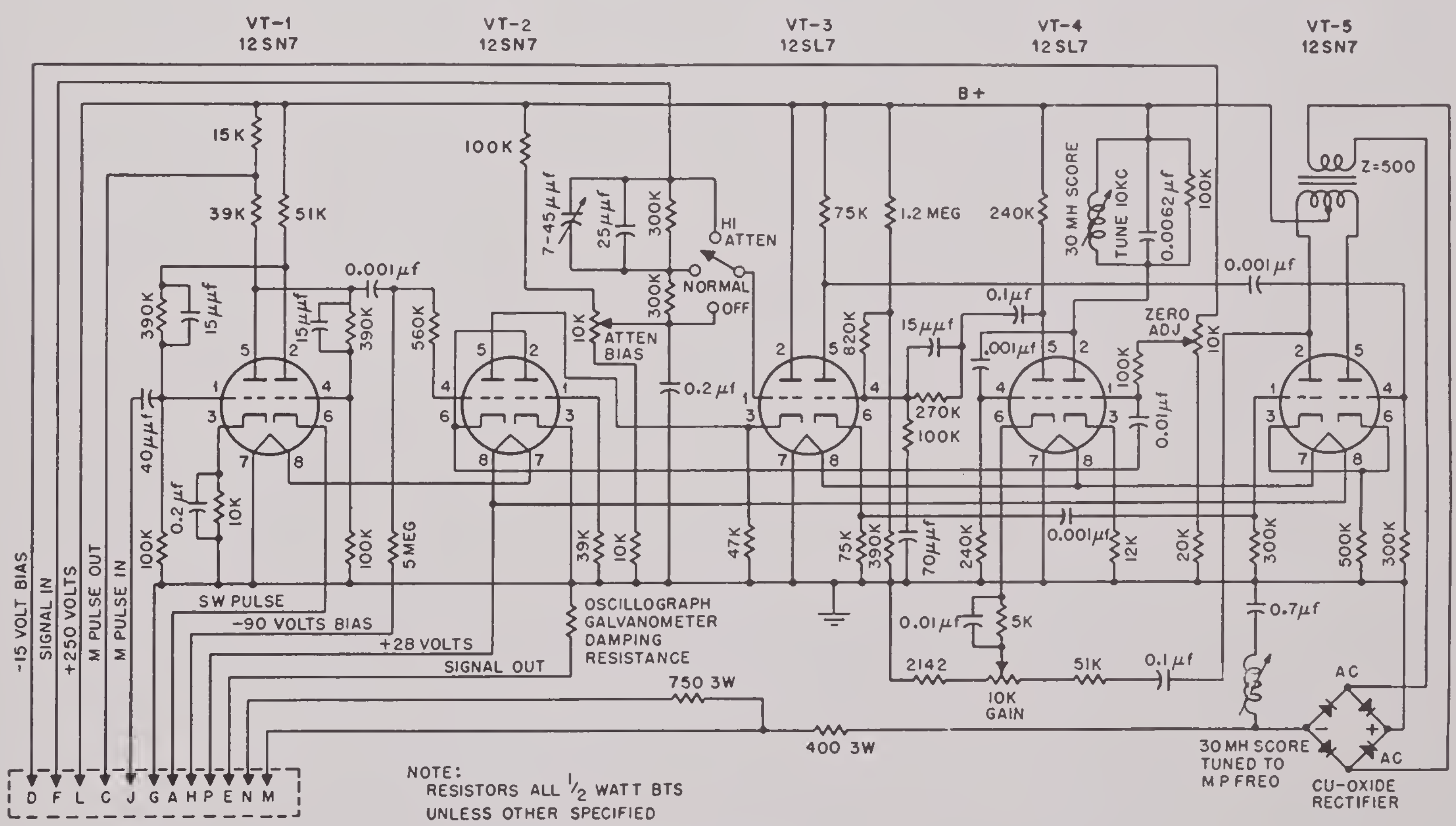

FIGURE 37. Receiver commutator channel (NDRC Type I, Model B).

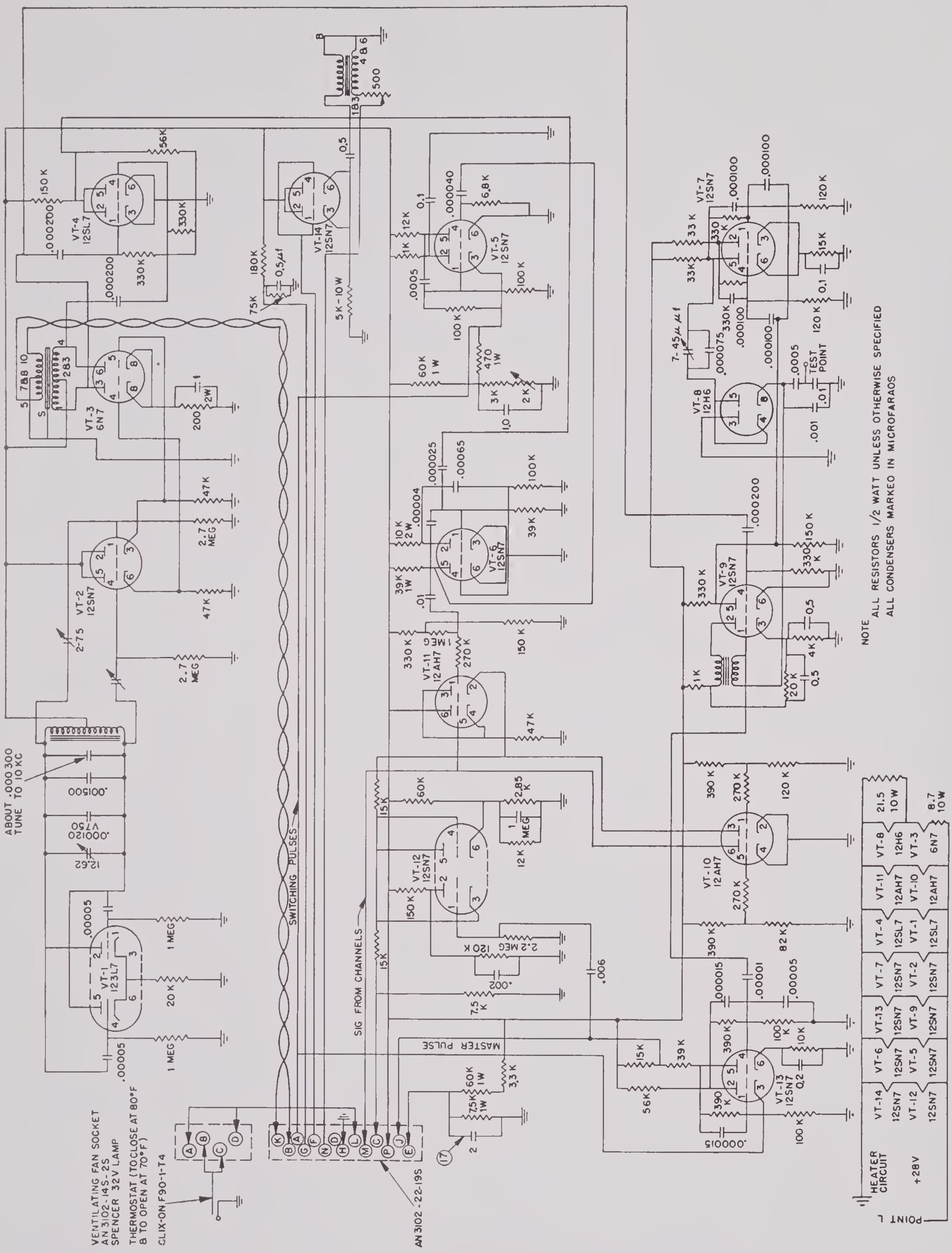

FIGURE 38. 10-kc pulse generator, Model M-5A (NDRC Type I, Model B).

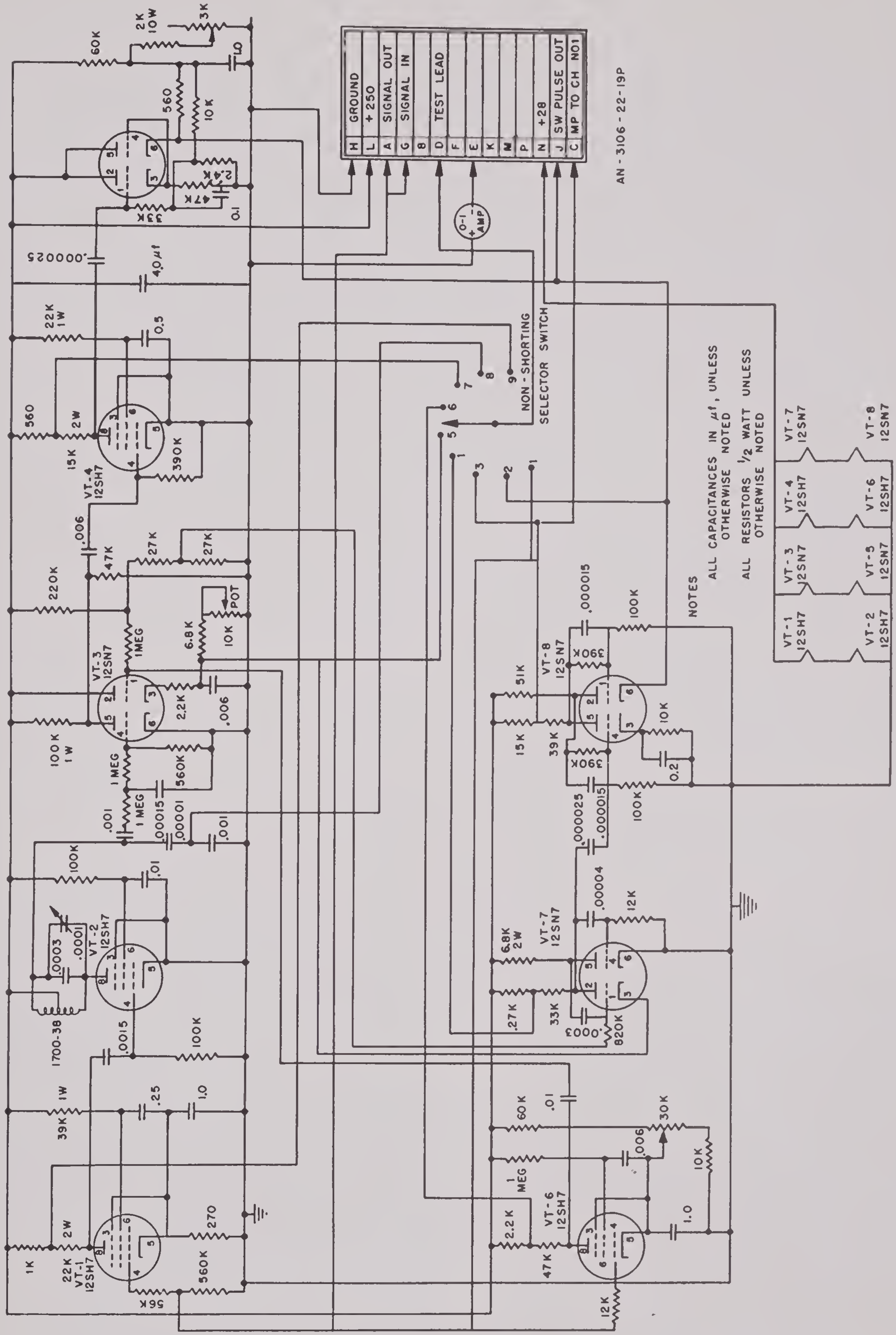

FIGURE 39. Pulse selector (NDRC Model I, Type B).

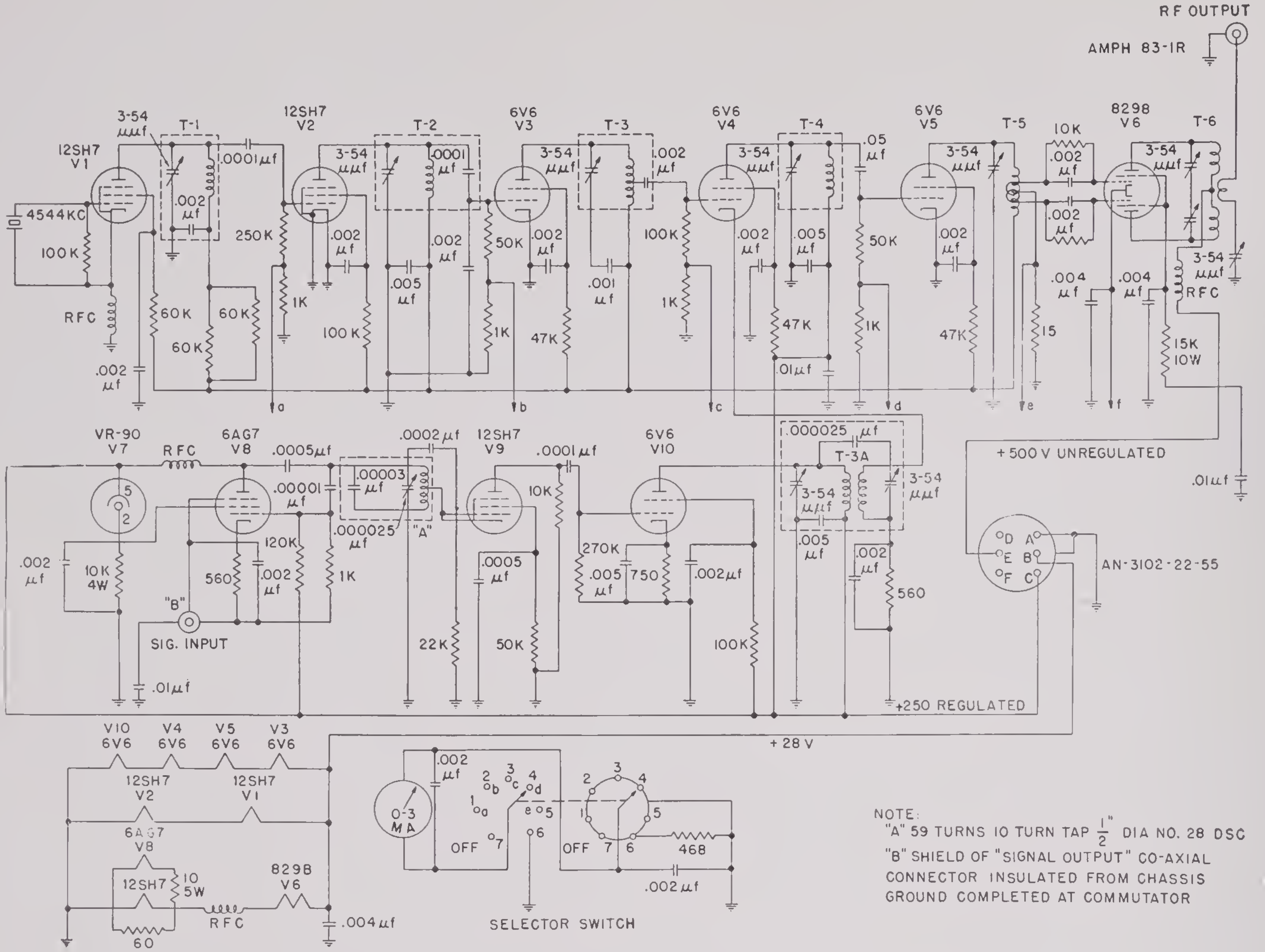

FIGURE 40. F-M transmitter, Model 1790 (NDRC Model I, Type B).

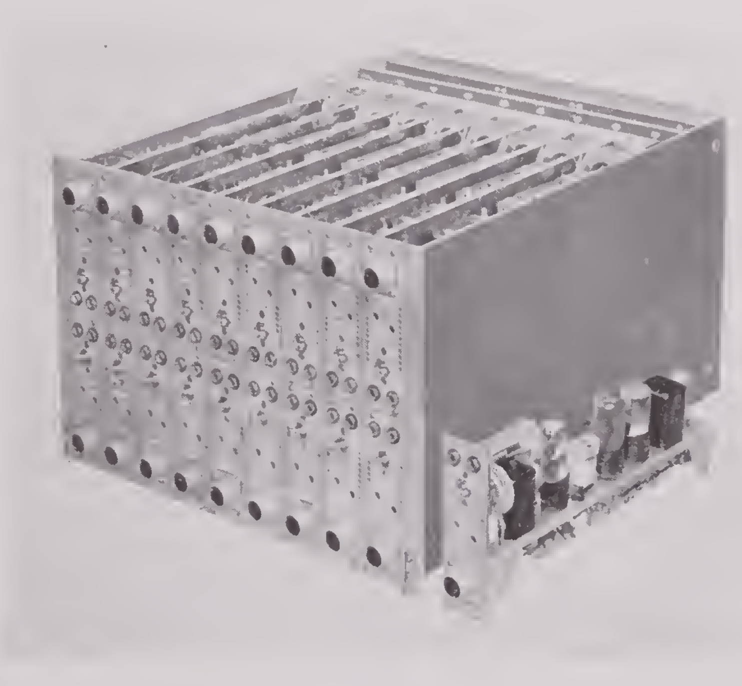

FIGURE 41. Front view of airborne commutator with dust cover removed (NDRC Type I, Model B).

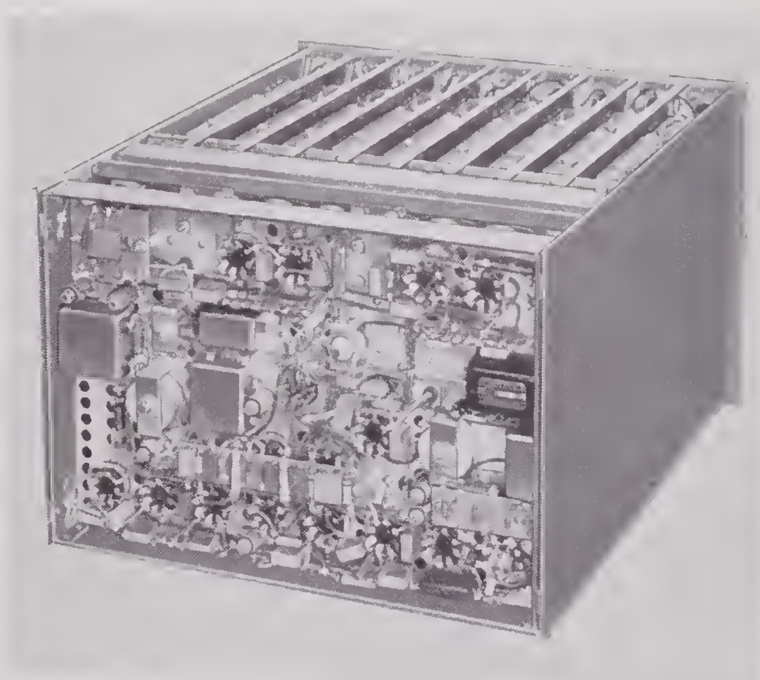

FIGURE 42. Rear view of airborne commutator and pulse-generator assembly (NDRC Type I, Model B).

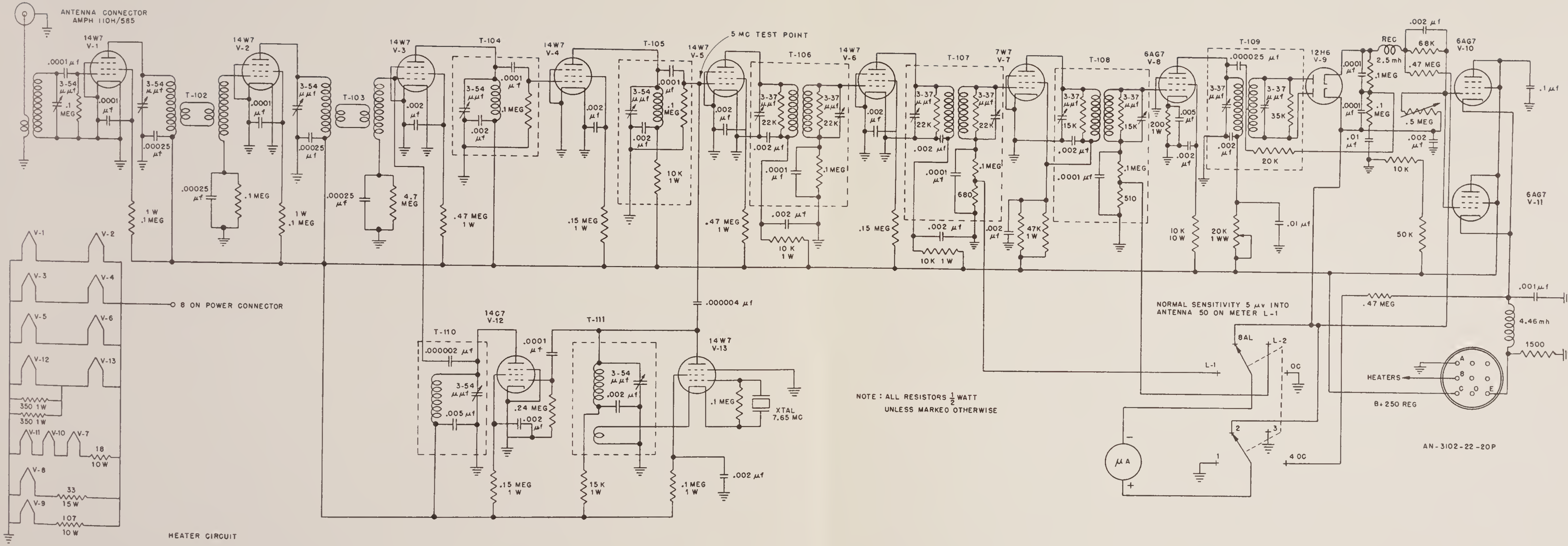

FIGURE 43. F-M radio receiver, Model 1789 (NDRC Type I, Model B).

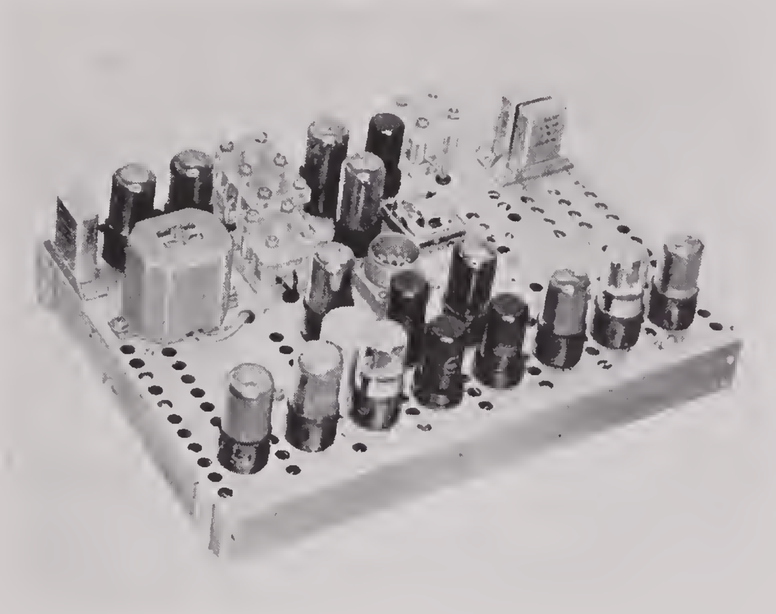

FIGURE 44. Pulse generator (NDRC Type I, Model B).

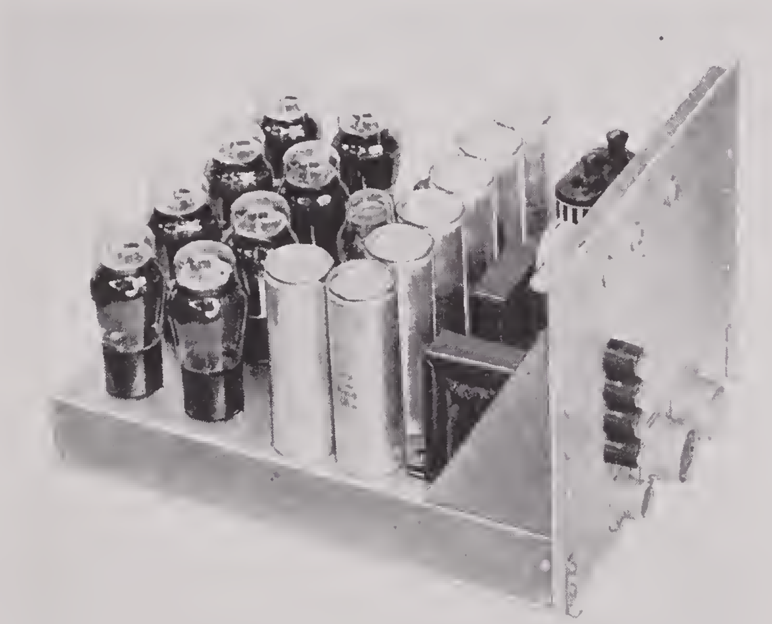

FIGURE 45. Airborne voltage regulator (NDRC Type I, Model B).

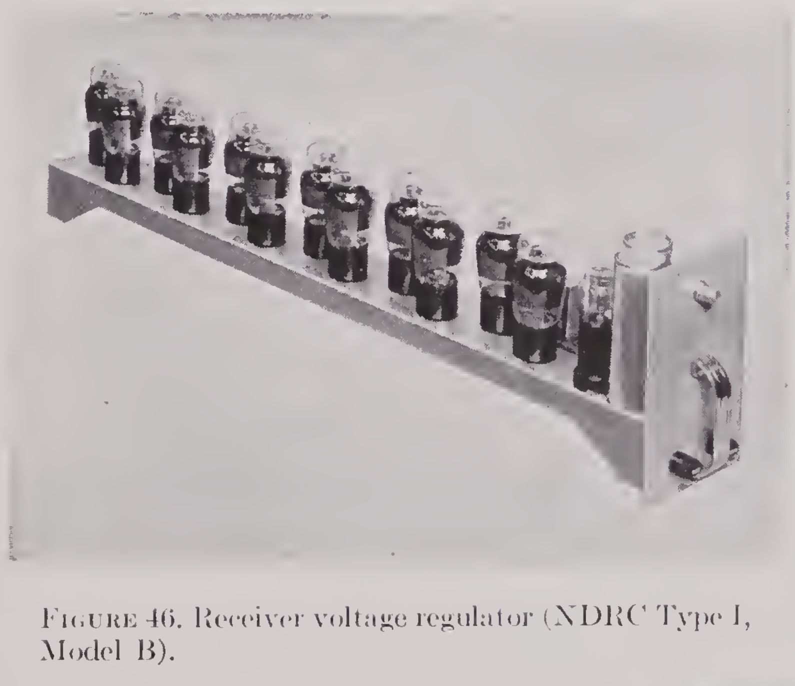

FIGURE 46. Receiver voltage regulator (NDRC Type I, Model B).

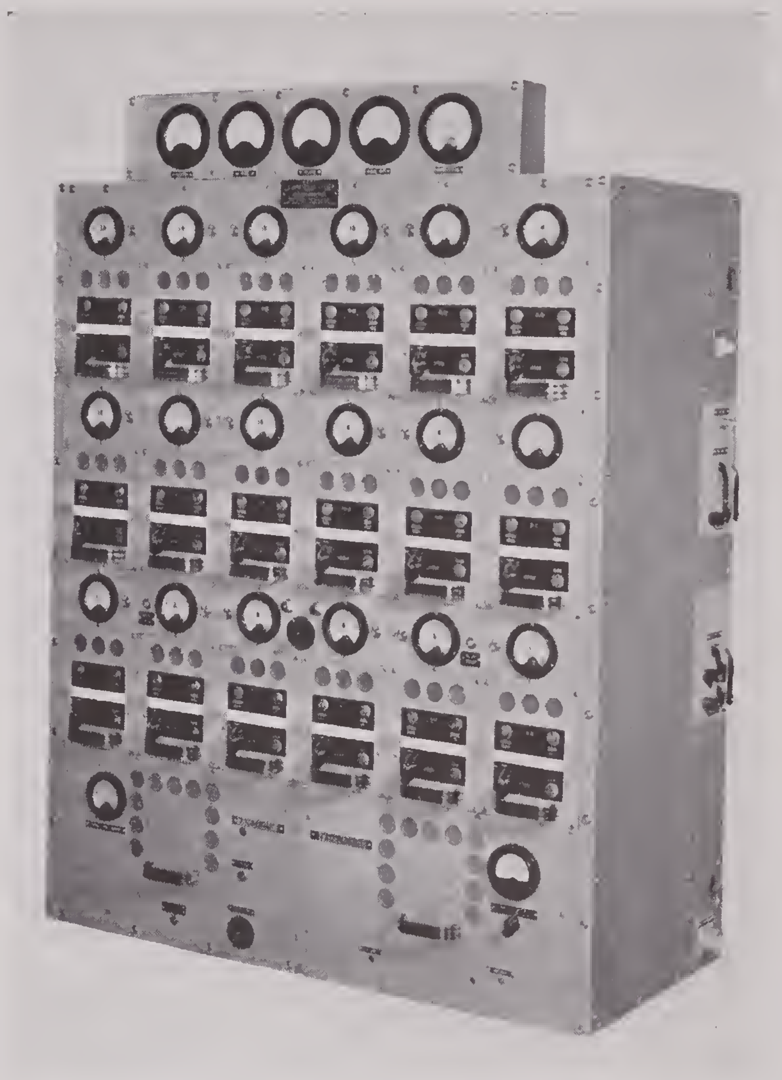

FIGURE 47. Complete receiver (NDRC Type I, Model B).

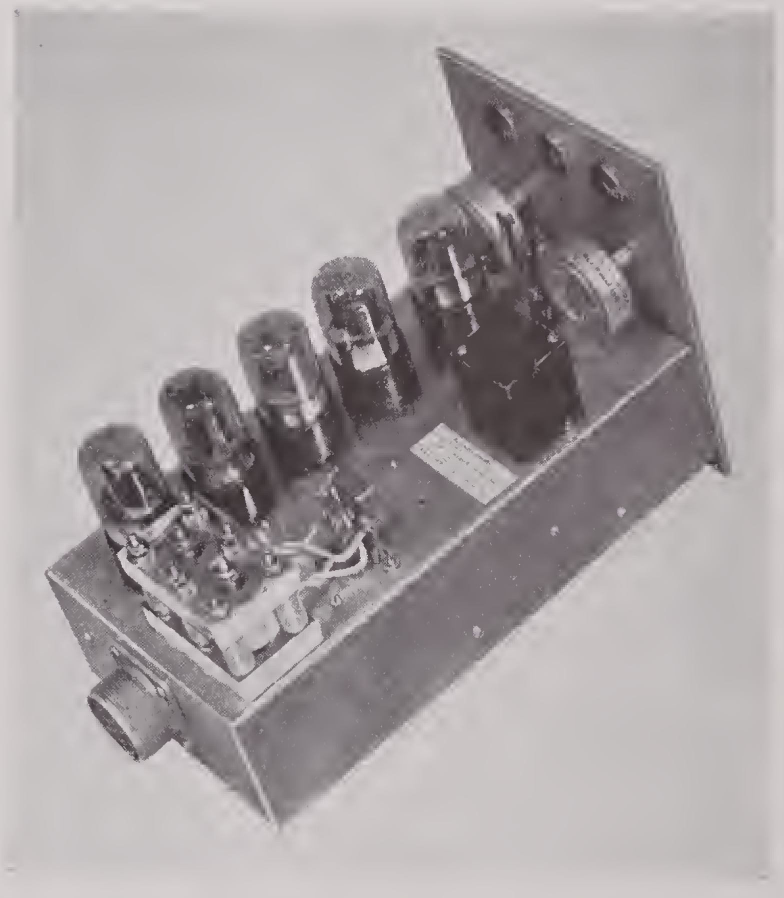

FIGURE 48. Receiver channel (NDRC Type I, Model B).

Chapter 2

THE ACOUSTIC FIRING ERROR INDICATOR [a]

By *J. W. M. Du Mond*[b] *and E. R. Cohen*[b]

2.1 INTRODUCTION

Under pressure of demand from three branches of the Armed Forces, research and development on the acoustic *firing error indicator* [FEI] and its associated auxiliary testing and standardizing equipment continued actively up to the termination date of the original Contract OEMsr-600, October 31, 1945. The progress of the work rendered nearly all interim and special reports more or less obsolete shortly after their appearance so that at the termination of the contract the need was imperative for a comprehensive report bringing all phases of the development strictly up to date if the value of the results achieved was not to be lost. For this reason, every effort has been made in the present report to furnish a complete and reliable source of all information which might be helpful (1) to administrative military and civil officials, (2) to the using Services, (3) to research groups entrusted with continuation of research and development work, and (4) to personnel of manufacturers of the equipment.

For the nontechnical reader the brief résumé following this introduction gives the salient facts at a glance. For his further information Sections 2.3, 2.4, and 2.5 have been written with a minimum of mathematical analysis and technical detail. Parts of Section 2.4, "Dependence of Shock-Wave Pressure Amplitude on Miss Distance" and "Dependence of Shock-Wave Period T' on Range (Projectile Velocity)" might be omitted on a first reading by such readers. Section 2.6 is nonmathematical and descriptive, but treats the FEI equipment and its functioning in considerable technical detail. Section 2.7 is purely historical.

The mathematical analysis has been kept almost entirely in the appendices.[c] Much of the technical information which would be required by manufacturers' personnel is placed there and also in Section 2.6 of the main body of the report. Appendix V is a collection of descriptive material on auxilliary standardizing and measuring equipment not described elsewhere in the report. This appendix will, therefore, be of interest to research workers who may continue the work, and also to some extent to the interested Services of the Armed Forces. The auxiliary measuring and standardizing equipment when built was accompanied by instruction manuals which were not formal NDRC reports.[33,35-38]

2.2 RÉSUMÉ

2.2.1 Purpose of Research

To develop a means of (1) scoring a gunner as to his marksmanship, and (2) informing a gunner (or his instructors) as to his errors when shooting at airborne targets such as towed flags, towed gliders or radio-controlled planes.

2.2.2 Basic Method

The amplitude of the ballistic shock wave propagated from the trajectory of the bullet is measured by a dual microphonic element installed in the target, and the result is transmitted by radio to a receiving station (near the gun), where the shots are automatically classified into three different zones of proximity to the target and so recorded either on a tape or on counters. The side (right or left, fore or aft) of the moving target on which the miss occurred is also indicated and recorded.

2.2.3 Limitations of Applicability of Present Device

1. Calibers: .50, 20 mm, 40 mm.
2. Bullet speeds at the target: 1,400 fps and higher.

[a] AC-46, NO-173, NO-260.

[b] California Institute of Technology.

[c] The appendices, to which references are made throughout the chapter, are the first five items in the bibliography associated with this chapter. As the appendices were voluminous it was decided to microfilm them for reference rather than to print them in this volume.

3. Targets: Velon plastic flags and towed gliders.
4. Target speeds: up to 250 mph.
5. Radio reception distances (target to receiving station): cannot exceed 4 miles.
6. Weather conditions: microphones rendered inaccurate by rain or ice formation.

For other and more detailed limitations see Section 2.5.5.

2.2.4 Validation Results

Validation tests checking the method against photographic theodolite data showed an accuracy in scoring miss distance of ± 7 per cent on 537 rounds fired at Ft. Bliss, Texas.

2.3 INTRODUCTION AND MILITARY REQUIREMENTS

2.3.1 Origin of the Need for a Firing Error Indicator

The greatly increased importance of the airplane in World War II has created a need for a method of indicating the errors of fire of marksmen and their equipment shooting at airborne targets both in ground-to-plane and in plane-to-plane shooting. The origin of the work on the present *firing error indicator* (FEI) was not, however, in a formal Service request for the device. It came as the result of certain ideas originating with members of the staff of the California Institute of Technology who had witnessed Army target practice in connection with other war research work. Their attention was thus forcibly called to the existence of the problem which may be stated as follows.

The aerial targets used in training gunners for World War II have necessarily been of rather small size, chiefly flags, sleeves, or gliders. These are towed at the end of a considerable length (several thousand feet) of cable by a special towing plane (usually a B-26) provided with a large motor-driven winch for reeling the cable, and a hatch in the bottom of the fuselage just to the rear of the winch, for launching the target after the towplane is in flight. To some extent small radio-controlled planes such as the OQ and PQ have also served as training targets. The number of actual hits which can be made on such targets is such an extremely small fraction of all rounds fired that no statistically significant information for comparing the marksmanship of different gunners or gun crews, or the relative merits of different kinds of equipment can be based thereon; nor can much reliable information be furnished (by observing holes in the target after a mission) to assist gunners materially in correcting their errors of fire. Experience has also shown that visual observation of tracer bullets fired at airborne targets is in general an unsatisfactory method either for training or for rating gunners.[d] The central difficulty in observing tracer fire is to determine when the tracer bullet has reached the range of the target, and this is especially true if the observer is at or near the gun.

2.3.2 The Importance of Training Gunners on Targets Permitting Large Scores

The fact remains that the two problems (1) of improving marksmanship by furnishing reliable and, if possible, instantaneous information as to errors of fire, and (2) of rating gunners and equipment with statistical reliability as to marksmanship performance, are of supreme importance in warfare. Even a small superiority in weapons or men, if it is really significant, cannot be ignored since it can be reflected as a relatively much larger advantage in actual combat, especially in situations which partake of the nature of a duel in which the more proficient survive. It is not only more humane to the gunners but far more efficient in the prosecution of the war if the best gunners and the best equipment can be selected with as much statistical certainty as possible. This seems a far more important consideration in scoring gunners and equipment than is the frequently heard proposition that the target on which the gunners are scored should duplicate in size the targets to be hit under combat

[d] Under certain special conditions as to course flown and observer position (situated at some distance down course from the gun) a special method worked out by the AAAS for ground-to-air firing permits visual estimates of the firing error in lead and lag by observation of the apparent hook in the tracer trajectory. However, this can hardly be regarded as a quantitative scoring device, and the fact that the use of tracer fire is regarded as a detriment in teaching marksmanship makes its application somewhat undesirable.

conditions. The problem of classifying gunners or rating their equipment is one of selecting those which are statistically more likely to give hits on the real target, and such a selection can be made more accurately and with fewer rounds if scoring targets are used which are considerably larger than targets usually simulating the size of those used in combat. It can be shown[30a] that targets of such size as to permit scores from 50 to 80 per cent hits afford the best accuracy (as to freedom from statistical fluctuation) in rating marksmanship performance.

It should be evident to anyone that targets so small that scores of only a few hits per thousand rounds can be registered, and targets so large as to permit only a few misses per thousand rounds are equally undesirable since such occasional hits or misses are likely to be statistical accidents rather than measures of average performance. Clearly then there must be, between these extremes, some optimum size of target. Analysis made under statistical laws shows that targets permitting scores of the order of 80 per cent are to be preferred for rating gunners on a relative scale of marksmanship as to their most probable miss distance. Targets permitting 50 per cent scores are nearly as good, but a 1 per cent target requires the firing of 60 times as many rounds for the same reliability as an 80 per cent target.

To tow a material target through the air at realistic speeds with sufficiently large dimensions to permit 80 per cent direct hits on it at normal working ranges is a practical impossibility. One of the chief advantages aimed at in the acoustic FEI is to furnish sensitive zones around the target center within which the passage of a shot will be indicated, such zones being large enough to permit the 50 to 80 per cent hit requirement.

2.3.3 Operating Principle of the Acoustic FEI

The method used in the present FEI to accomplish this result relies on the fact that projectiles, as long as their speed relative to the air mass substantially exceeds the speed of sound, send out from their trajectories acoustic waves known as ballistic shock waves. The intensity of these shock waves at a given point is a diminishing function characteristic of the distance of the point from the trajectory of the bullet. A microphonic element, known as the FEI transmitter and mounted in the airborne target, has been developed which sends a quantitative signal to the FEI receiving station indicative of the intensity of the shock waves from the bullets passing in the vicinity of the target. This signal is interpreted at the receiving station by automatic means into information regarding the proximity of the round to the target. Since two oppositely directed microphones are used in the FEI transmitter, indications can also be furnished regarding the directionality (i.e., angular direction) of the misses, though such indications are only reliable under certain limitations as to the obliquity of the shooting. An FEI transmitter, mounted in a rectangular opening provided for it in the center of a 4x20-ft flag target is shown in Figure 1. The two microphones can be seen on the right and left sides of the spherical housing of the FEI transmitter. When the microphone-pair axis is placed parallel to the direction of tow, indications as to whether misses are leading or lagging the target can be given.

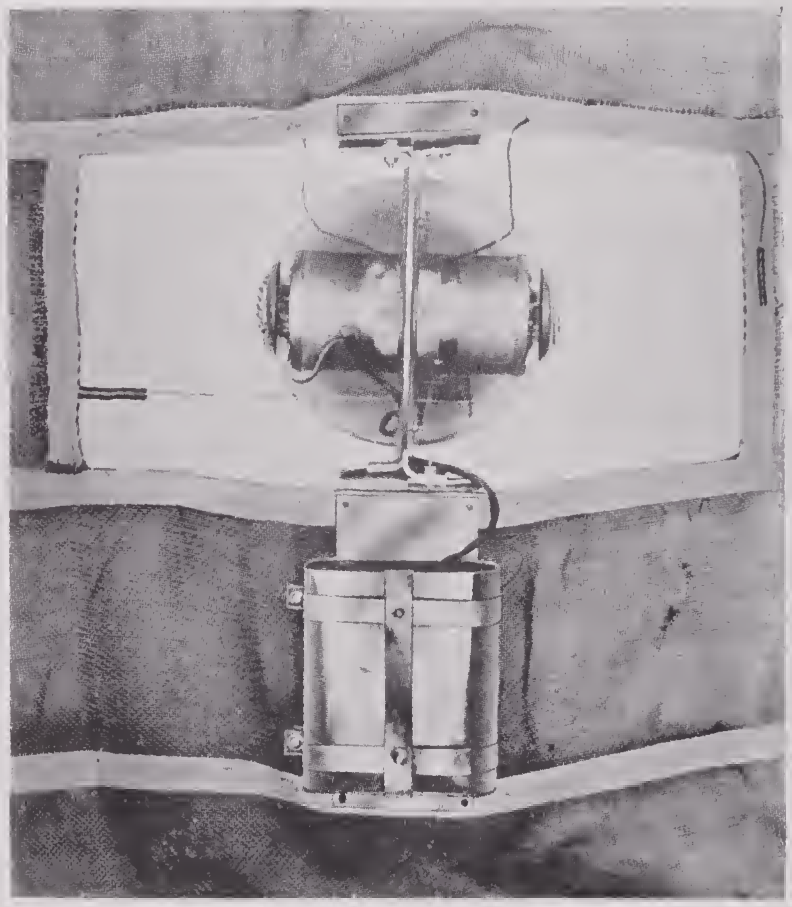

FIGURE 1. Aperiodic FEI transmitter mounted in center of 4x20-ft Velon plastic flag target.

The sum of the responses of the two microphones to the ballistic shock wave is known as the *sum response*, and because of the acoustics of the spherical encasement the sum response turns out to be an index of the miss distance independent of the orientation of the microphone-pair axis relative to the bullet trajectory. In the figure one of the two batteries can be seen (attached on either side of the flag just below the transmitter). The two radio antennas lead upward from the transmitter and the string is attached through a spring to one edge of the rectangular hole. When the flag unfurls as it is streamed this string operates a switch so that the batteries are turned on to operate the FEI transmitter.

2.3.4 The Two Functions of the FEI, Scoring and Informing, Contrasted

From the foregoing, two distinct functions of the FEI become rather clearly defined, namely, (1) *scoring* gunners and equipment, by which a quantitative statistical measurement rates the subjects on a relative scale of marksmanship performance in as statistically reliable a way as possible, and (2) *informing* which is of a more qualitative nature, where the object is to inform a gunner or his instructors, with as little delay as possible, as to the nature of the errors of fire as they are being committed, chiefly with the idea of accelerating the training of the individual. This information may, for instance, consist in telling an aerial gunner, after each burst of machine-gun fire, whether his shots fell to his right or left of the target and in what order such misses occurred. If a very close round was indicated by the FEI (within some roughly specified bull's-eye distance), then this information may also be furnished and the round number indicated. By such means the gunner can be expected to correlate the information as to his errors and as to his more successful rounds, with his memory of the appearance of the target in his sights and the other pertinent circumstances of the occasion so as to build up habits of proficiency. This will obviously be most effective if a minimum time elapses between the shooting and the information. Clearly the informing function concerns single rounds (or a small burst) and is not statistical. It requires little more than qualitative accuracy in the device. Qualitative unreliability regarding single rounds, however, would be a rather serious source of confusion to the trainee gunner.

The scoring function, on the other hand, requires a device which will define in all cases a target of nearly the same size so that scores made by different gunners and equipment with different FEI's will be comparable. Here the radial size of the effective target is the element of chief interest and statistical reliability is required rather than qualitative single-shot reliability.

In the present FEI the scoring of gunners has been identified with nearly circular concentric zones of sensitivity around the target center within each of which the passage of a bullet is recorded. Thus, the ability to indicate or measure radial miss distances independent of direction has come to be identified with the scoring function. This, however, is partly a result of the physical nature of the FEI as developed and is not to be considered as a primary definition of scoring. On the other hand, the qualitative indication of the directionality of the errors of fire (e.g., whether the miss is fore or aft of the target if the towing is transverse, or is to the gunner's right or to his left, above or below the target, etc., as the particular application may require) has come to be associated with the informing function, though here again this is not its primary definition. The qualitative round-to-round indications of close hits (within some specified radial distance) is clearly also part of the informing function.

This function has been chiefly emphasized in the training of aerial gunners shooting from plane to plane because here the training concentrates on individuals rather than on groups, and the information can therefore be most effectively used to accelerate learning. Because of the many things which a gunner must think about while shooting, it has been generally agreed that the instantaneous information supplied to him by the FEI must be of a very simple qualitative nature. The indication of a close hit and of one of two opposite directions of miss seems to be about as much as a gunner

could be expected to profit by in view of the complicated and distracting nature of his activity.

To summarize then, the scoring function of the FEI calls for a statistically significant and quantitative means of measuring and indicating the number of rounds which fall within concentric circular zones around the airborne target center, so that gunners and equipment can be compared as to marksmanship results. The informing function of the FEI calls for qualitatively correct indications to gunners or their instructors, from round to round, as to the nature of their errors of fire while they are being committed or immediately thereafter. Scoring is statistical, and aims at rating marksmanship. Informing is nonstatistical and aims at training marksmen.

2.3.5 Different Phases of the Problem Arising from Various Service Interests

The Service interests in the FEI have been chiefly the following: Antiaircraft Artillery, the Air Forces, and the Navy (ship-to-plane fire and plane-to-plane rocket fire). The Air Force interests may be subdivided into fixed gunnery (the training of fighter pilots) and flexible gunnery (the training of waist or turret gunners shooting from bombers at attacking fighter planes).

Antiaircraft Artillery

The Antiaircraft Artillery [AAA] represents the interest of the Army Ground Forces which was the first and most active interest exhibited on the part of the Services. We list below various requirements and conditions imposed by the AAA needs.

Types of targets requested. Towed sleeves, flags, and gliders and OQ and PQ radio-controlled model planes. The use of towed sleeves was largely abandoned before the final form of the FEI was developed which was primarily for use in towed flags of Velon fabric[e] and in a Navy type of towed glider, the 16-ft winged target Mark I Model 1. Formal Service request for the OQ and PQ model plane application originated too late to permit completion of this development. It was definitely established in tests, however, that the noise of the motor and propeller on the model planes did not interfere with the operation of the FEI at the shock-wave amplitudes for which it is designed.

Towing speeds. From 125 to 250 mph. A great deal of towing is done at present just below 200 mph.

Calibers. Caliber .50 and 40 mm were first requested and the FEI has been developed for these. Interest in larger calibers and much higher altitudes (for the targets) has been expressed but time has not permitted this development.

Target scoring zone sizes. At the outset it was very difficult to find representative magnitudes of gunners' radial miss distances. Choice of scoring-zone radii had to be made from rather rough guesses. The final choices of FEI zone dimensions, made after much experience with the FEI in actual shooting, have been compromises between the best size of target from the statistical point of view and the need to stay sufficiently close to the transmitter to keep the shock-wave intensities high in comparison to accidental disturbances, noise, etc. Zone boundaries are defined at three different radii. For .50 caliber the zone radii are 2½ yd, 5 yd, and 10 yd. For 40 mm the radii are 4, 15, and 25 yd.

Types of course. In antiaircraft target practice the guns are usually located at intervals along a firing line. Transverse courses are then towed parallel to this line at perhaps 1,000 to 1,500 yd slant range above the guns. The guns fire in succession as the target passes by, each gun ranging over a horizontal angle of perhaps ±45 degrees either side of the perpendicular to the course. Incoming courses are also though less frequently used in which the plane tows the target at right angles to the firing line, passing nearly directly over some of the guns. Random, irregular, or unexpected courses have rarely been used.

Power supply. 110-v 60-c alternating current from battery M.G. sets driven by gasoline engines.

[e] Much work was done in an effort to use metal wire mesh flags, the metal cloth itself being used as the radio antenna, but with rather unsatisfactory results. The Velon material makes a more durable target and its insulating qualities permit the use of straight wire antennas threaded into the cloth with which very satisfactory radio transmission is obtained.

Aerial Gunnery (Flexible Gunnery, Bomber-to-Fighter Fire)

The training here is concentrated upon individual gunners and the general emphasis on informing is greater since the learning problem is a very difficult one because of the motion of both firing plane and target. The rapid changes in tactics with the changing needs of the war made it difficult to keep both FEI and target development for aerial gunnery abreast of new requirements. For example, at the outset, training on targets such as sleeves or flags flown parallel to the shooting plane were contemplated but later this was replaced by "pursuit-curve" courses in which the target executes a course more or less simulating the curve of pursuit which an attacking fighter must fly in order to keep his own fire directed at the bomber. Still later the use of large bomber formations (in which flexible gunners were required to shoot at fighters not necessarily attacking their own planes) tended to render the pursuit-curve training course obsolete and to necessitate more random types of course for the targets. The adoption of pursuit-curve courses led to the abandonment of flag targets since the course is directed nearly head-on along the gunner's line of sight and the flag, seen on edge, is nearly invisible. For this reason the Navy towed glider (16-ft winged target) was adopted and certain features of the FEI had to be somewhat redeveloped for this new target. These shifting trends have modified requirements as to the type of informing desired. Starting with lead-lag informing (telling whether shots are fore or aft) the emphasis shifted to right-left informing and then to above-below informing for the pursuit-curve courses. It is difficult, if not impossible, with the FEI in its present state of development, to adapt it to informing as to directionality of miss for a random, unpredicted course, although informing as to close hits and scoring, for reasons which we shall see later, can still be furnished satisfactorily for such random courses. A list of requirements imposed by more recent flexible gunnery needs is listed below.

Types of target requested. Towed gliders[f] for pursuit-curve training were requested, with an FEI transmitter mounted on projecting struts in front center and with gimbal mounting permitting different orientations of the microphone axis.

In Figure 2 an FEI transmitter is shown in the gimbal mounting on the supporting struts which project forward from the nose of the fuselage and carry the batteries. By moving bolt holes in the gimbal mounting a wide choice of orientations for the microphone-pair axis is available. The antenna wires extend laterally from either side of the FEI transmitter to the forward projecting tips of struts mounted on either wing tip. These struts should be long enough to support the antenna wires nearly perpendicular to the axis of the glider in order to obtain a sufficient range of angles over which transmission is strong for both radio channels.

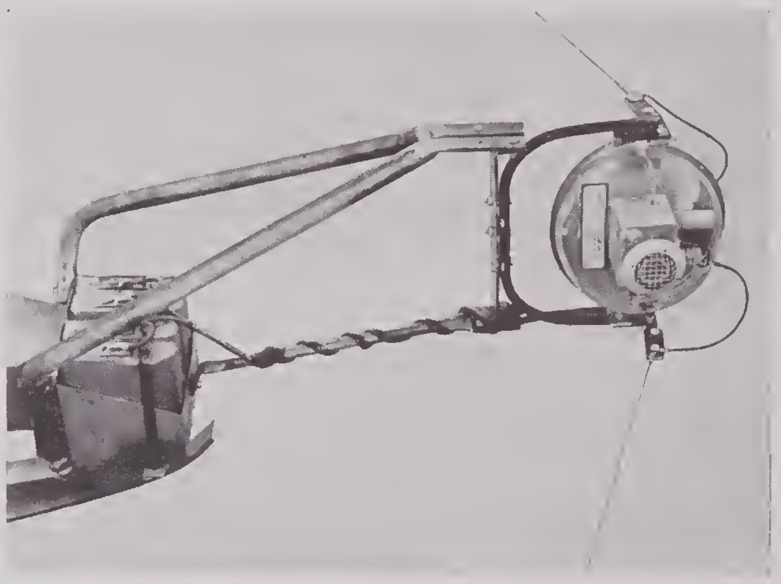

Figure 2. Aperiodic FEI transmitter mounted in towed glider target.

Towing speeds. From 125 to 250 mph.

Calibers. Caliber .50 only.

Rate of machine-gun fire. Up to 20 rounds per second. The present FEI can furnish and record separate data on each and every round at this rate but no faster. Signals occurring at closer intervals than 1/20 second interfere in the electrical circuits of the receiver. In turret fire, therefore, with two guns firing in random relation to each other, this is likely to occur. Hence use of only one gun is recom-

[f] Gliders must have conductive coatings beneath the fabric cover removed. These coatings, usually supplied to give radar reflection, interfere with the effectiveness of radio transmission of FEI signals.

mended, or else the guns must be synchronized and timed to permit no two rounds closer than 1/20 second. By somewhat more elaborate circuits in the receiver this minimum resolving time could probably be diminished tenfold, but time has not permitted this improvement.

Target scoring zone sizes. Zones of radii 2½, 5, and 10 yd.

Types of course. Pursuit curve and random courses.

Location of receiving station. In B-29 or B-17 bomber.

Power supply. Primary supply 24-v direct current. This necessitates use of an inverter to give 110-v alternating current in order that the same design of receiving station can be used as the receiver for the Ground Forces. A standard inverter which has worked successfully for this has 0.75-kva output at 400 c, 115 v (normally used for power supply to automatic pilot).

Fixed Aerial Gunnery

The requirements in fixed gunnery are very ill-defined because no actual use of the FEI has been made by this Service branch to date. Interest is still shown by them however. The fixed gunnery application of the FEI differs from the flexible one in that the course flown by the target is straight but the angle of the bullet trajectories with that course varies over a very wide range. Thus the "aspect angle" as it is called, namely the complement of the angle between the bullet trajectory and the axis of microphone pair in the FEI transmitter, varies over a very wide range and, for reasons which will be more evident later, this is likely to render unreliable the indications of the directionality of firing errors for at least part of the time. Scoring, however, and informing as to proximity of hits remain reliable. Another way in which fixed aerial gunnery probably differs from other FEI applications is that the receiving station cannot conveniently be situated in the gunner's plane both because of space limitations in the fighter plane, and because a separate operator for the FEI is desirable, and fighter planes are frequently one-man machines. The proposed solution is to situate the FEI receiving station in the towing plane from which the FEI operator relays the information regarding the gunner's errors to the gunner over the regular radio communication set after each pass or burst of machine-gun fire.

As regards towing speeds, targets, calibers, and power supply, the fixed aerial gunnery requirements are probably identical with those listed for flexible aerial gunnery.

Navy

At the outset, the Navy interest in the FEI was indicated solely for target practice in ship-to-plane fire. The proposal to use it in training with plane-to-plane rocket fire did not arise until 1944, and, as suitably fast and accurate plane-to-plane rockets had not as yet been developed, realization of this purpose has been necessarily retarded. Existing rockets for plane-to-plane shooting only barely reach practical shock-wave velocities if fired forward from an already rapidly moving plane. As very little is known about ballistic shock waves from rockets, experimental work using static firing with the FEI was carried out. The FEI transmitter was mounted on wires between poles so that shots could be fired at known miss distances from it. It was also necessary to provide an elaborate installation with rocket-propelled launching carriages operating on 350-ft rails, to give the rockets the required initial velocity. These facilities were under construction by the Navy at the Naval Ordnance Testing Station at Inyokern, California, but because of the pressure there of higher priority work the facilities were not completed by the termination of the NDRC contract. Continuation of the work by Navy personnel is contemplated.

In ship-to-plane fire a large number of guns fire from the very concentrated area of the ship's deck at a plane which is usually approaching directly toward the guns because the ship itself is usually the target. Hence, for simulated ship-to-plane practice the courses flown by the tow plane are almost entirely those in which the target passes nearly directly over the gun. Because of the great concentration of guns used no great effort was directed at the problem of training or rating individuals

or single gun crews in marksmanship. The training stations were usually situated on a shore with many guns concentrated in a small area simulating the deck of a ship. The targets, usually sleeves or flags, were towed toward the land, so that the shooting was over the water. Clearly under such conditions the applicability of scoring, save for the entire group, is out of the question since there is no way of discriminating between the shots. Hits within a few yards of the target were shown by trial with the FEI to be so rare that the above-mentioned resolving time of the device (1/20 second) was sufficiently short (to avoid confusing two hits as one) but no way exists to indicate which gun should be credited with the close hit.

The above reasons, coupled with unsatisfactory performance of some of the earlier models of FEI transmitter, resulted in a less active Navy interest in the device than was the case with other Service branches. On the other hand the application to plane-to-plane rocket fire, as already stated, got under way so late that there has been little opportunity for its development under this contract.

2.4 RESEARCH ON BALLISTIC SHOCK WAVES AND THEIR APPLICATION TO THE FEI

Before passing to a description of the FEI and its results, some space must be devoted to the nature of ballistic shock waves, acoustic-response patterns of the transmitter, the types of field tests required, etc. This offers the best opportunity to build up a set of basic concepts and terminology which will be used henceforth throughout the report. Another purpose is to give the motivating reasons for the designs finally developed.

2.4.1 Ballistic Shock Waves, Their Nature and Laws of Propagation

After a considerable amount of purely empirical work on two early forms of the FEI (see Section 2.7), an extensive program of pure research work on ballistic shock waves was necessary in order to explain the surprising results observed and to permit a more intelligent approach to a satisfactory design. We give in the following section a brief review of well-known pertinent facts together with some of the results of this pure research.

General Description of Shock Waves

The ballistic shock wave from a bullet is an intense acoustic phenomenon occurring only in the case of bullets whose speeds relative to the surrounding air exceed the velocity of sound. It is analogous to the V-shaped head and stern waves which occur when a ship is propelled rapidly through water.

It is possible to photograph shock waves directly and by this means they have been shown to be a right circular cone traveling forward with the speed of the bullet (see Figure 3).

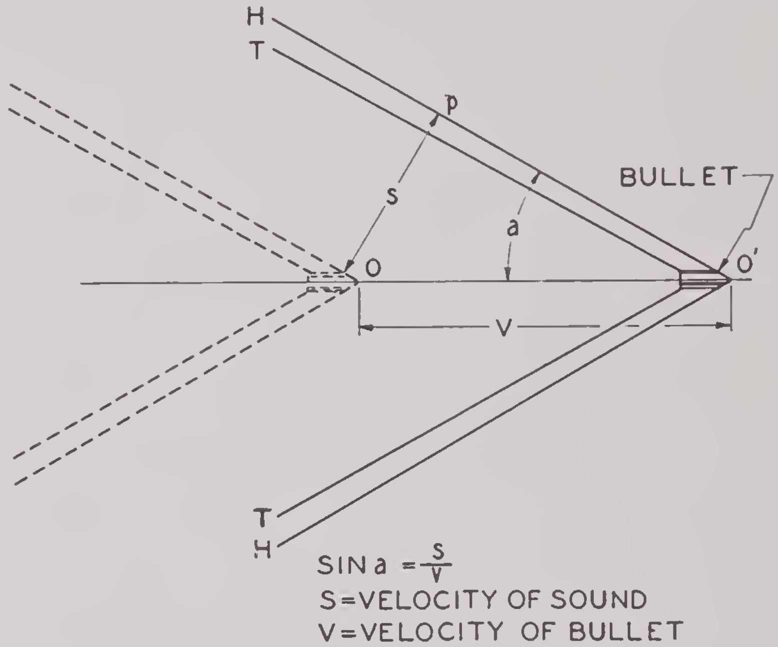

FIGURE 3. Geometry of shock-wave formation.

The bullet plows aside the air which then streams back to fill up the void. In the region of the nose, therefore, there is set up a wave of condensation which radiates laterally from the trajectory while from the tail there is set up a wave of rarefaction which radiates similarly. The propagation of these two disturbances takes place at a velocity approximately that of ordinary sound in a direction normal to the conical shock-wave front. (Actually, the head wave is propagated slightly faster than sound while the tail wave is slightly slower.) Suppose that the full lines in Figure 3 represent the position of the bullet with its accompanying shock wave 1 second later than their positions as shown by the dotted lines. In the 1-second interval while the nose of the bullet progressed through a distance v from O to O',

the pressure disturbance traveled a lesser distance, S, from O to p. The distance v is numerically equal to the velocity the bullet (e.g., in ft per second) while S is numerically equal to the velocity of the acoustic shock wave in the same units. Thus the angle a, the semi-apex angle of the shock-wave cone, is more acute the faster the speed of the bullet. It can be computed from the approximate formula,

$$\sin a = \frac{s}{v}. \tag{1}$$

Source and Propagation of Shock-Wave Energy

The source of the shock-wave cone is obviously the trajectory of the bullet. As illustrated in Figure 4, each foot of trajectory (e.g.,

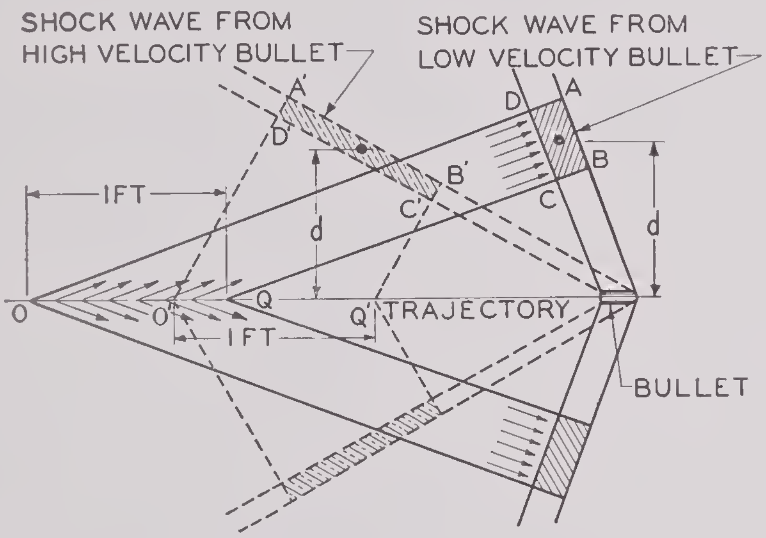

Figure 4. Energy transfer from trajectory to shock wave. The case for a bullet whose velocity is only slightly above sonic velocity (full lines) is compared with that for a bullet with higher velocity (dotted lines). In the case of the low-velocity bullet, the flow of shock-wave energy from one foot of trajectory is indicated with arrows. At the instant shown, the shock-wave energy is in the volume of revolution swept out by rotating the shaded areas about the trajectory as axis.

OQ) may be thought of as contributing a section of the shock wave, namely the volume which would be swept out by the shaded area $ABCD$ if the latter were rotated around the axis OQ. The source of the very appreciable acoustic energy propagated outward in this expanding conical volume is the kinetic energy lost by the bullet in traversing the segment of its trajectory OQ, and indeed it is probable that a major fraction of the force exerted by the bullet in overcoming so-called air resistance, performs the work of forming the shock wave. The small remainder of the work done by the bullet against air resistance is converted directly into heat and, to a small extent, into forward-streaming velocity of the air.

Shock waves are not formed by bullets whose velocities are below the velocity of sound. In such cases the energy lost by the bullet is still given to the air in much the same way as before but no sharply defined conical front is formed.[g] At bullet velocities only slightly higher than sonic the semi-apex angle of the shock-wave cone is nearly 90 degrees. It is valuable to point out in this connection that for such a case the source of the energy which forms the shock wave may be a part of the trajectory at a considerable distance to the rear of the bullet. The geometry of this situation is shown in Figure 4 by the full lines. It is clear also from this figure that the energy converted into shock-wave energy from the segment OQ is, even at the same miss distance, concentrated in a smaller volume of space than is the case for higher-velocity bullets, the latter case being shown by the dotted lines in Figure 4. It is probable that this in part explains the observed fact that the shock-wave intensities do not diminish greatly with diminishing bullet velocity until the latter comes very close to the velocity of sound.

Wave Forms of Shock Waves

The wave forms of shock waves from bullets of calibers .30, .50, 20 mm, and 40 mm were carefully investigated during this work. Two types of a very high-speed microphone were used. These microphones controlled the y-axis deflection of a cathode-ray oscilloscope whose x-axis motion was furnished with a "single-sweep" motion. This single-sweep motion was triggered by the shock wave itself through the agency of a second microphone placed so as to

[g] If, at a specified instant, spheres of radii st_1, st_2, st_3, etc., are drawn around points of the trajectory occupied by the bullet t_1, t_2, t_3, etc., seconds earlier to indicate how far sonic disturbances, originating at each of these positions and instants of time, would have been propagated, then it is easy to see that for bullets whose speeds are greater than sonic these spheres intersect each other to form a sharply defined conical envelope which is the shock-wave cone; whereas for bullets whose speeds are less than sonic none of the spheres intersect each other, each being completely enclosed by its predecessor, so that no sharply defined wave front is formed.

receive the shock wave a little earlier than the recording microphone. Although the wave forms obtained from such studies have many smaller complex irregularities, certain salient features of similarity can be clearly distinguished in the case of all the calibers studied. These are now discussed because they are important for an understanding of the action of the acoustic FEI. Figure 5 shows with some idealization how the

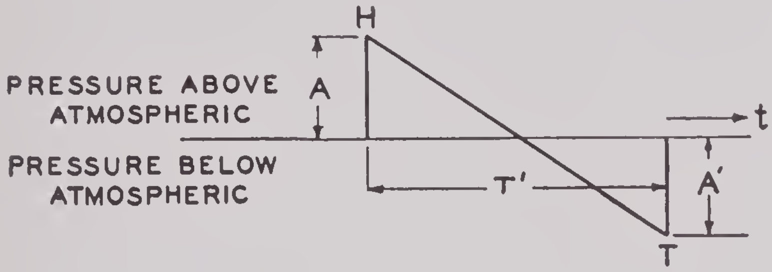

FIGURE 5. N-shaped shock-wave profile. Acoustic pressure at fixed point in air plotted as function of time.

pressure on a stationary microphone diaphragm varies with time as the shock wave passes. This same profile therefore can also be understood to represent a cross section of the pressures existing in space throughout the thickness of the shock-wave cone at a given instant of time (with, of course, a reversal of sense and a change of scale on the abscissa). There are two very abrupt discontinuities of pressure, the head and tail (shown at H and T) and the *energy* of the shock-wave disturbance is localized between them. In the photographs of shock waves these discontinuities or fronts appear as the two very sharp conical boundary lines. These lines are never exactly parallel, but diverge slightly with increasing distance from the bullet. The H front is a sudden rise above atmospheric pressure set up by the sidewise thrust of the bullet. The pressure then declines more or less linearly to a value equally far *below* atmospheric, and then returns very abruptly to normal, (the tail discontinuity T). The inrush of air at the tail of the bullet is caused by the atmospheric pressure trying to fill the void created by the transit. The abrupt nature of the tail discontinuity does not develop until after the shock wave has been propagated a foot or so from the trajectory. The process whereby this occurs is an important one for the understanding of finite sound waves of this type, and is explained below.

Shock-Wave Discontinuities or Fronts; Their Formation and Propagation

When the pressures and condensations in sound waves become appreciable fractions of atmospheric pressure and density, it is a well-known fact that the portions of the wave *above* atmospheric pressure have velocities slightly in excess of the ordinary velocity of sound, whereas the portions *below* atmospheric pressure have velocities slightly less. The reason for this is clear. In the portions of the wave where the pressure is above atmospheric there is a particle velocity in the forward direction, and the velocity of sound propagation relative to this moving air is, if anything, slightly higher than in other parts of the wave because of the higher temperatures in the high-pressure regions. This velocity of sound is therefore added to the local particle velocity to give the velocity at which the elevated portions of the wave form in such a region are propagated. Similar reasoning shows that the negative portions of the wave form are propagated below sonic velocity. There is thus a differential in the velocity of propagation of the various parts of the wave profile so that in the regions of positive acoustic pressure, the higher portions "catch up" on the portions near atmospheric pressure, while in the negative regions the lower portions of the wave form lag behind those nearer to atmospheric pressure. As this process progresses, the rising portions of the wave form become steeper and steeper (and the falling portions, less and less steep) until the wave form eventually becomes vertical, or nearly so, at some point.

The wave form or pressure profile can obviously not pass beyond the vertical, for if it did this would imply two pressures at the same point in the air at one time. In fact, the so-called discontinuity never becomes completely abrupt although its thickness may become excessively small for large pressure transitions. The thickness is limited by two effects, viscosity and thermal conductivity, which counteract the steepening tendencies, previously described, by transferring heat and momentum across the wave front when a certain limiting abruptness has been reached. For weak shock waves (pressure steps of the order of a few per cent of one atmosphere) the thickness of the front is inversely proportional to the amplitude of the pressure step. See Table 1 farther on in this section for representative front thicknesses which are of the order of fractions of a millimeter for the ballistic shock waves with which we are concerned.

As other portions of the wave form catch up with this discontinuity they coalesce with it and add to its height. Crossing over this front by other portions of the wave profile never occurs. Each new and higher segment of the wave form that arrives at the discontinuity merely makes the discontinuity higher with a consequent slight increase in its velocity of propagation. Similar statements may be made regarding the building up of the tail wave. Each new and lower segment of the wave form lags behind until it reaches the discontinuity and it then merely increases the amplitude of the tail discontinuity with a consequent slight decrease in its velocity of propagation (relative to the undisturbed air mass). Figure 6 is a

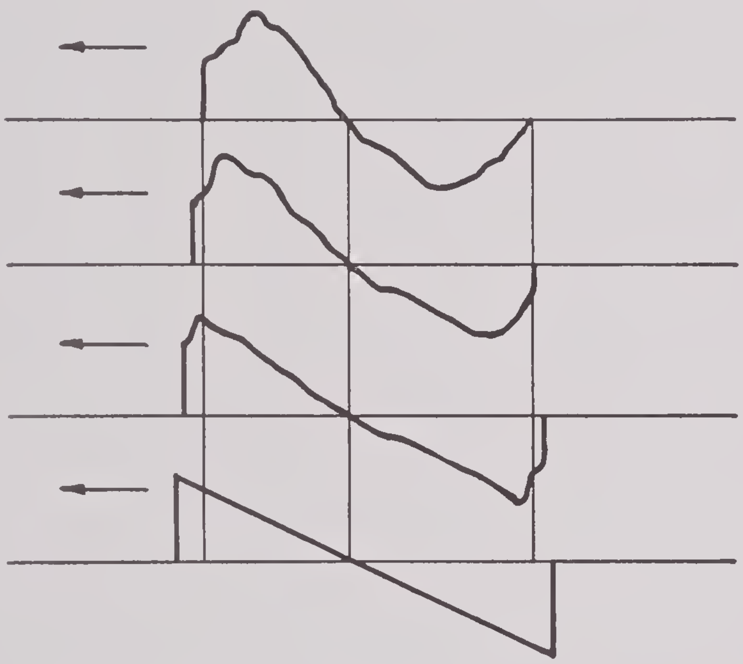

FIGURE 6. Progressive changes in wave form as ballistic shock wave is propagated to left.

sketch illustrating the progress of such a process.[h] This progressive joining of various parts of the wave profile to form the two discontinuous fronts can also be clearly seen on the direct photographs of shock waves.

The advance of the crests and the retardation of the troughs in the wave profile have an analogy in surface waves on water as they advance toward a shore over a sloping beach, but in the latter case the wave profile on the forward side can pass beyond the vertical so that a breaker is formed. In the case of sound waves this is impossible since it would imply more than one pressure at a given point in space.

The discontinuities just described are the most characteristic features of a shock wave. They are completely different from any wave form occurring in the case of ordinary sounds. It is also clear because of the above-mentioned sharp discontinuities that there may be present in ballistic shock waves, even after they have traveled 60 to 80 yd, Fourier components of very high frequency. In ordinary sound waves such high frequencies are very rapidly absorbed, but in the case of shock waves, the steepness of the fronts is maintained in spite of such absorption by the effects just outlined.

It is clear from a study of Figure 6 that a large variety of initial wave forms will, by the process just explained, eventually assume approximately the N-shaped profile.

Amplitudes Associated with Ballistic Shock Waves

It is possible to obtain a measure of the amplitude of the discontinuities of the N wave by observing the rate at which the period, T', of the N wave (measured between the H and T discontinuities) increases with increasing miss distance. Because of the difference in velocity between the H and T discontinuities, there is a progressive change of this period T' and the spatial separation between the two fronts with increasing distance from the trajectory. For the case of 40-mm fire this shock-wave period has been found to be twice as long at 80 yd from the trajectory as it is at 4 yd.

The experimentally established fact of the differential in the speeds of propagation of the two discontinuities extending as it does out to such large distances, together with the characteristic N-shaped wave profile and the description of its formation are, it is believed, little-known and valuable contributions to the knowledge of shock waves made as by-products of the research and development on the acoustic FEI. Since this work was done attention has been called to the work of L. D. Landau.[43] He describes a wave form of this type which theoretical considerations led him to expect as the eventual profile of a shock wave after propagation over large distances.

Were it not for the doppler effect which modifies this period for a moving microphone the best way by far for measuring miss dis-

[h] The reader is referred to Appendix III[3] for a detailed account and a theoretical treatment of the formation of the discontinuities. The velocity of propagation of a discontinuity is there shown to depend on the amplitude of its pressure step according to the Rankine-Hugoniot discontinuity relationship.

tance would, no doubt, be by observations of this period. The curves of Figure 7 show, on logarithmic coordinates, how the period T' of the shock wave increases with increasing distance from the trajectory. These curves were

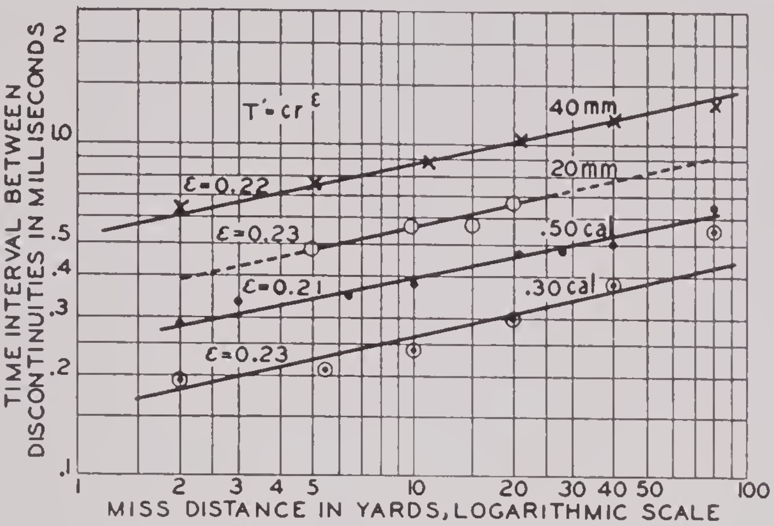

FIGURE 7. Period of shock wave versus miss distance.

plotted from measurements of the shock-wave period T' made on oscillograms. The periods for four calibers are shown. It should be noted that all the curves have such a slope on logarithmic paper as to indicate that T' increases approximately as the fourth root of the miss distance.[3]

Because of this change in N-wave period with miss distance, one of the earlier attempted forms of the FEI, in which highly resonant diaphragms were used in the microphones, had very peculiar acoustic-response characteristics. The highly resonant diaphragms of 1,600- and 2,400-c frequencies were provided, with the idea of using a single r-f channel of communication, and distinguishing between the signals from the two microphones in a bilateral FEI transmitter by tuning the diaphragms to different audio frequencies. With these resonant diaphragms it turned out that at certain miss distances an unfavorable ratio between diaphragm period and N-wave period actually resulted in complete unresponsiveness of such diaphragms, while at other miss distances their response was greatly enhanced. In the case of 40-mm caliber fire, with a 2,400-c resonant diaphragm, a null response actually occurs at very close miss distances of the order of 1 yd, and again at 20 yd, and a maximum of response occurs at about 2½ yd and again at 40 yd. Figure 8 shows such a response curve. Although this figure was computed theoretically from a solution of the differential equations for the motion of the diaphragm, as acted upon by an N wave having the periods observed (Figure 7), it turns out to be very satisfactorily checked by experiment. The null points referred to have been observed by actual shooting as has also the intervening maximum point. These results furnish confirmation of the general picture of the ballistic shock-wave propagation process.

POSSIBLE EXISTENCE OF "AFTER WAVES"

Before leaving the subject of wave forms it should be mentioned that there is possible evidence of some acoustic disturbances trailing to the rear of the N-shaped wave profile. These are only very faintly visible, if at all, on the direct photographs of shock waves but are to be seen in some of the oscillograms, immediately following the tail discontinuity. They seem to be of a very irregular nature and are not very definitely related in phase or wave form to the N shape itself. Curiously enough,

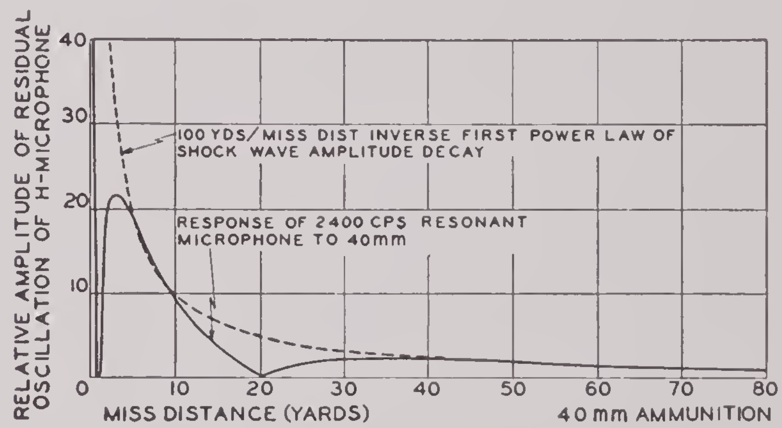

FIGURE 8. Theoretically computed response curve versus miss distance.

the process whereby the H and T discontinuities are built up in the N wave does not seem to be operative to form similar discontinuities in these "after waves." We are unable to explain this at present. In fact, the entire nature and origin of the after waves is obscure. It may even be that they are not really present in the air but are in some fashion a parasitic effect coming perhaps from vibrations set up in the microphones.

DEPENDENCE OF SHOCK-WAVE PRESSURE AMPLITUDE ON MISS DISTANCE

The microphone measurements of the peak pressure elevations in shock waves as a func-

tion of *miss distance* (the perpendicular distance from the trajectory measured to the point of observation) show that these pressure elevations vary inversely as the nth power of the miss distance where n has the value $n \geqslant \frac{3}{4}$. Since the energy density in the wave is proportional to the square of the pressure elevation this implies that the energy density falls off as the inverse 1.5 power (or faster) of the miss distance. This is a somewhat faster rate of decay with distance than would be expected if (1) there were no dissipation of shock-wave energy into other forms, and (2) the thickness of the N-shaped wave form (measured between the H and T fronts) were not progressively increasing. Were the two causes not operative the simple geometry of shock waves (Figures 3 and 4) would give an inverse first power law of dependence of energy density on miss distance and an inverse one-half power law for the peak excess pressure. The theoretical reason for the observed dependence is given in Appendix III.[3]

Absolute Values of Shock-Wave Pressure Amplitudes

Estimates have been made of the absolute values of the peak pressure elevations in shock waves, based on the rate of increase of the N-wave period T', and using the Rankine-Hugoniot discontinuity relationship between propagation velocity and pressure elevation. These agree as to order of magnitude with estimates based on the response of the microphones. For shock waves at 40 yd distance from the path of the bullet they indicate, as shown in Table 1, very high momentary sound intensities of the order of a million times the intensity of ordinary speech at 1 yd distance, for example.

In the table, formulas are given in terms of δ, the peak pressure elevation in the shock wave expressed in fractions of the atmospheric pressure.

$$\delta = \frac{p_2 - p_1}{p_1}\,, \tag{2}$$

where p_1 is the undisturbed atmospheric pressure and $p_2 - p_1$ is the height of the pressure step in the two N-wave discontinuities (which are assumed to be substantially equal). The numerical fractions in each formula are in reality functions of the specific heat ratio, γ, for air. The values used for δ in computing Table 1 are obtained by observing the slope of the curve relating T', the N-wave period, with miss distance. This method, which we call the $\partial T'/\partial d$ method, relies on the fact that the excess and defect in the propagation velocities of the H and T discontinuities of the N wave are related to their pressure-step amplitudes by the Rankine-Hugoniot discontinuity relationship which for weak discontinuities assumes the simple approximate form

$$\frac{\epsilon - c}{c} = \frac{3}{7}\,\delta\,. \tag{3}$$

ϵ is the propagation velocity of the discontinuity, and c is the propagation velocity for ordinary sounds.

Table 1. Absolute ballistic shock-wave magnitudes for air.

	Formula for shock-wave magnitude	40 mm at 40 yd miss distance	.50 cal. at 40 yd miss distance	Ordinary speech at 1 yd
Peak pressure elevation dynes/cm² (lb/in.²)	$p_2 - p_1$	2200 (0.032)	1500 (0.022)	2 (0.00003)
Max particle velocity cm/sec	$5/7\,\delta c$	52	35	0.05
Max temperature rise C	$2/7\,\delta T_1$	0.19	0.13	0.0002
Peak intensity watts/cm²	$5/7\,\delta^2 p_1 c$	0.0115	0.0052	10^{-8}
Shock-wave discontinuity thickness cm	$3 \times 10^{-5}\,\delta^{-1}$	0.014	0.020	....

Reproducibility of Transmission of Shock-Wave Amplitudes Through Outdoor Air

The reproducibility with which shock-wave amplitudes are transmitted through outdoor air over large distances, such as 10 to 40 yd, is higher than experience with ordinary sounds might lead one to anticipate. In making measurements of the shot-to-shot reproducibility of the response of the FEI, several other causes beside the irreproducibility of shock-wave transmission are simultaneously operative and difficult to separate from the latter. These are the irreproducibility of bullet velocity, of miss distance, of transmission of shock waves through outdoor air, of FEI-transmitter and receiver response, and of the graphs from the recording instrument. Clearly, the variation in transmission can contribute only a fraction of the total observed shot-to-shot variability of response. The simultaneous operation of all six of these sources of irreproducibility is some 6 or 7 per cent for the case of a transmitter in still air. In towed flight there seems indication that the reproducibility is less satisfactory probably because of pressure disturbances, turbulence, etc. For the stationary transmitter an upper limit of the standard deviation arising from the irreproducibility of transmission of shock waves through outdoor air alone is probably not more than 5 per cent of the mean observation and perhaps very much smaller than this. These figures, holding for distances of propagation of the order of 40 yd, represent much higher reproducibility than is encountered for ordinary infinitesimal sounds. The explanation is perhaps to be found in the large particle velocities, pressure amplitudes, temperature rises, and condensations associated with shock waves, which perhaps far exceed the accidental local fluctuations of air velocity, pressure, temperature, and density encountered in outdoor air.

Dependence of Shock-Wave Amplitude (Peak Value) on Projectile Caliber

The measurements with calibers .50, 20 mm, and 40 mm indicate that the relative peak amplitudes of the shock waves from bullets of these three different calibers referred to the peak amplitude of caliber .50 as unit are as given in Table 2, for distances of about 10 yd from the trajectory. These ratios are applicable to the three calibers in question over a range of miss distance from 5 to 20 yd.

Table 2. Relative shock-wave magnitudes.

.50 cal	1.00
20 mm	2.0
40 mm	3.8

Dependence of Peak Value of the Shock-Wave on Projectile Velocity

The variation of shock-wave amplitude with range from the gun (and therefore with projectile velocity) is extremely small, so small in fact that it is difficult to be certain whether the variation is not due to errors of measurement. With increasing range from the gun it becomes increasingly difficult to place shots correctly as to miss distance and also increasingly difficult to estimate the error of placement with theodolites. For example, at 1,500-yd range and for the case of 40 mm for which $n = 0.9$, an error in fire of 1 mil results in a 15 per cent error in miss distance at a miss distance of 10 yd, with a consequent error in shock-wave amplitude of about 0.9 of this amount (13.5 per cent). Such errors are difficult to avoid.

Table 3 shows typical data regarding the variation of shock-wave amplitude with range

Table 3. Range variation of sum response of aperiodic microphone transmitter to shock waves from three different calibers.

Range from gun in yd	40 mm at 20 yd miss distance speed fps	40 mm at 20 yd miss distance response	20 mm at 10 yd miss distance speed fps	20 mm at 10 yd miss distance response	.50 cal. at 10 yd miss distance speed fps	.50 cal. at 10 yd miss distance response
250	2,610	4.52	2,245	2.07	2,325	3.01
500	2,430	5.74	1,790	2.21	2,190	2.81
1,000	2,100	4.61	1,220	1.47	1,725	2.44
1,500	1,800	4.31			1,320	3.84

from the gun for calibers .50, 20 mm, and 40 mm. The approximate projectile speeds at these ranges are also tabulated.

Dependence of Shock-Wave Period, T', on Range (Projectile Velocity)

The period T' (between H and T discontinuities of the shock wave) which one might at first glance expect to be inversely proportional to projectile velocity turns out to be surprisingly insensitive to velocity. It has not been possible to establish satisfactory evidence for any dependence of this type whatever. In Appendix III[3] it is shown that an absolute relationship between shock-wave amplitude and period and miss distance containing no arbitrary constants whatever drops out of the theory for the case of large miss distances in a somewhat surprising way. This relationship is satisfied by the experimental observations to within the range of their accuracy. It is a matter of doubt[3] to what extent the position of the tail discontinuity and the wavelength of the shock wave can be regarded as determined by the length of the bullet and to what extent, especially at large distances from the trajectory, these must be regarded as determined by the laws of propagation.

2.4.2 Pure and Developmental Research Methods and Equipment

Field Tests with Static Firing

A very large amount of field testing known as "static firing" has been required for the pure research and also the developmental work in connection with the FEI. In static firing the microphonic element is not towed through the air but a detector of suitable design is suspended by wires on one or more poles about 25 ft above the ground on a firing range. Shots are fired at measured ranges and miss distances from this, either to measure the shock-wave amplitude or to ascertain the *response patterns* of an FEI transmitter. It is desirable to define a few terms which will be constantly used both in connection with static firing and elsewhere. The *target plane* is an imaginary plane passing through the FEI transmitter perpendicular to the *gun target* [GT] line (straight line from gun to FEI transmitter).[i]

Response patterns of the FEI transmitter are plotted in this plane. Curves of *iso-response* can be plotted in this plane, i.e., the loci of the piercing points in the plane of bullet trajectories which excite the same response in the FEI transmitter. These form a complete system of loci descriptive of the response characteristics for one aspect angle or orientation of the FEI transmitter relative to the direction of shooting. Such response patterns must be studied for different aspect angles, for different ranges and for different calibers. A great many rounds must be fired because, besides the necessity of exploring response as a function of so many variables, it is also necessary that each shot be duplicated five or six times in order to average out statistical fluctuations in shock-wave response. Because of inaccuracy in firing, somewhat more shots must usually be placed that can be used. The placement of each shot in the target plane is observed with two BC scopes (battery command telescopic theodolites) which are provided with horizontal and vertical scales in the field of view so that the error in placement of the shot (right or left and in elevation) relative to the desired point in the target plane can be recorded. The BC scopes are situated, one at the flank and one directly behind the gun, preferably on towers, the flank scope being used as a check on elevation and the rear scope as a check on right or left error. The range is provided with surveyed markers indicating standard horizontal miss distances in the target plane. The method generally employed for supporting the FEI transmitter utilizes a specially designed light, tubular supporting framework which permits orientation of the transmitter in measurable orientations in polar coordinates without offering serious obstacles to the sound waves. This frame runs on an oblique funicular trolley cable from the ground up to the top of the pole by means of a rope and pulleys, the

[i] A more strictly accurate definition of the target plane should specify it as perpendicular to the trajectory of a bullet making a direct hit on the FEI transmitter. The difference between these definitions is slight for the close ranges used at present but may become important if larger calibers and higher altitudes are used.

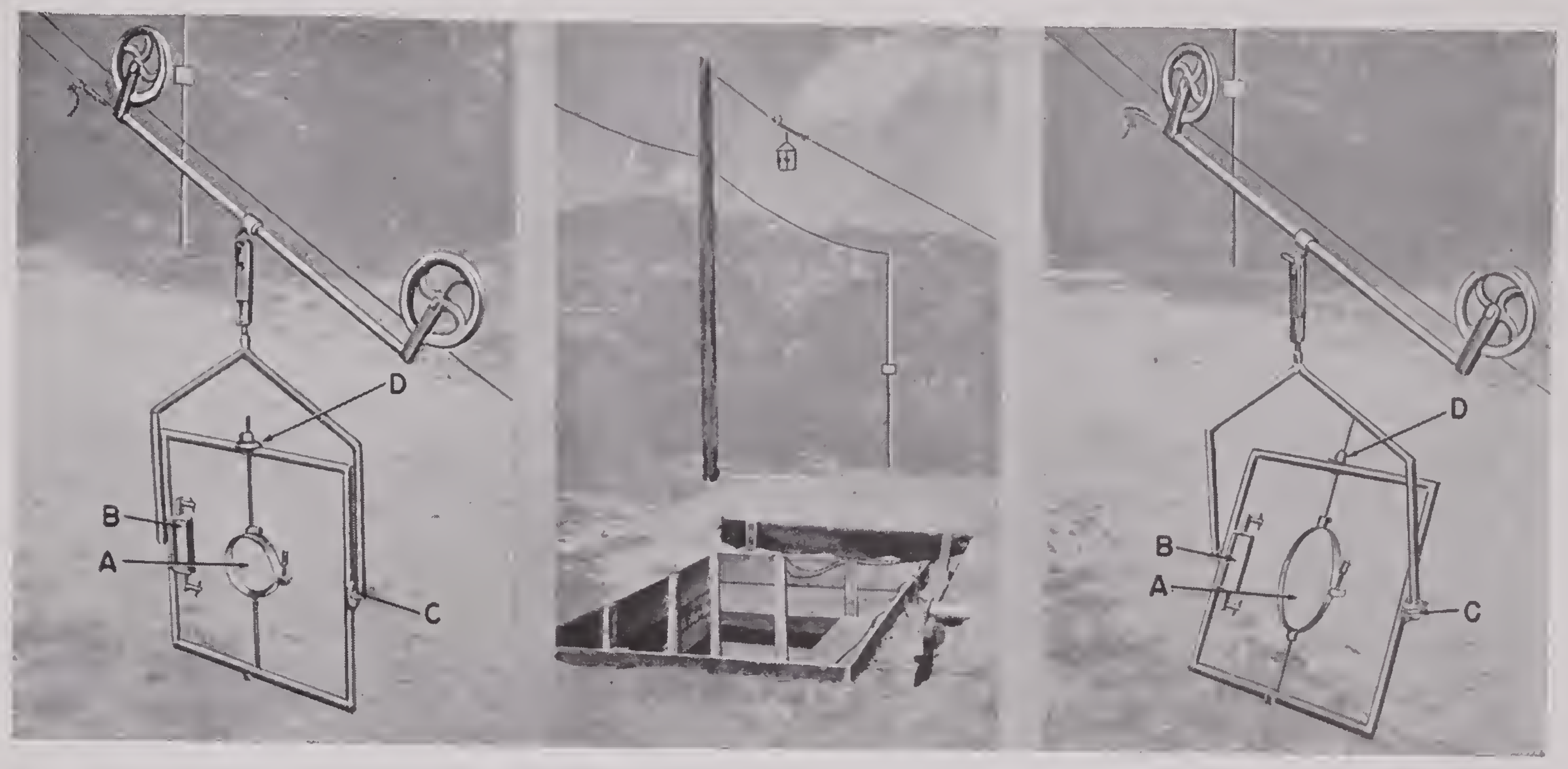

FIGURE 9. Funicular trolley and Lincoln range.

vertical plane through the oblique cable being parallel to the direction of shooting on the range. Three photographic views of these arrangements on a small-caliber experimental range near Pasadena are shown in Figure 9. At C and D the protractor scales for measur-

FIGURE 10. Perspective view of Camp Irwin range.

ing the polar coordinate angles of orientation of the transmitter are shown. *A* is a clamping ring provided for holding the transmitter and, *B* a clamp for the batteries. In one of the views the "fox hole" where the measuring instruments and observers are situated is visible. In Figure 10 is shown a perspective view of the general layout of the Camp Irwin range where the bulk of the research was done, and Figure 11 shows the range and launcher as planned at the Inyokern Naval Ordnance Testing Station for the special work with rockets. At the latter range the transmitter trolley operates on one of a set of horizontal wires strung transversely across the range between pairs of poles at different distances in front of the launching position.

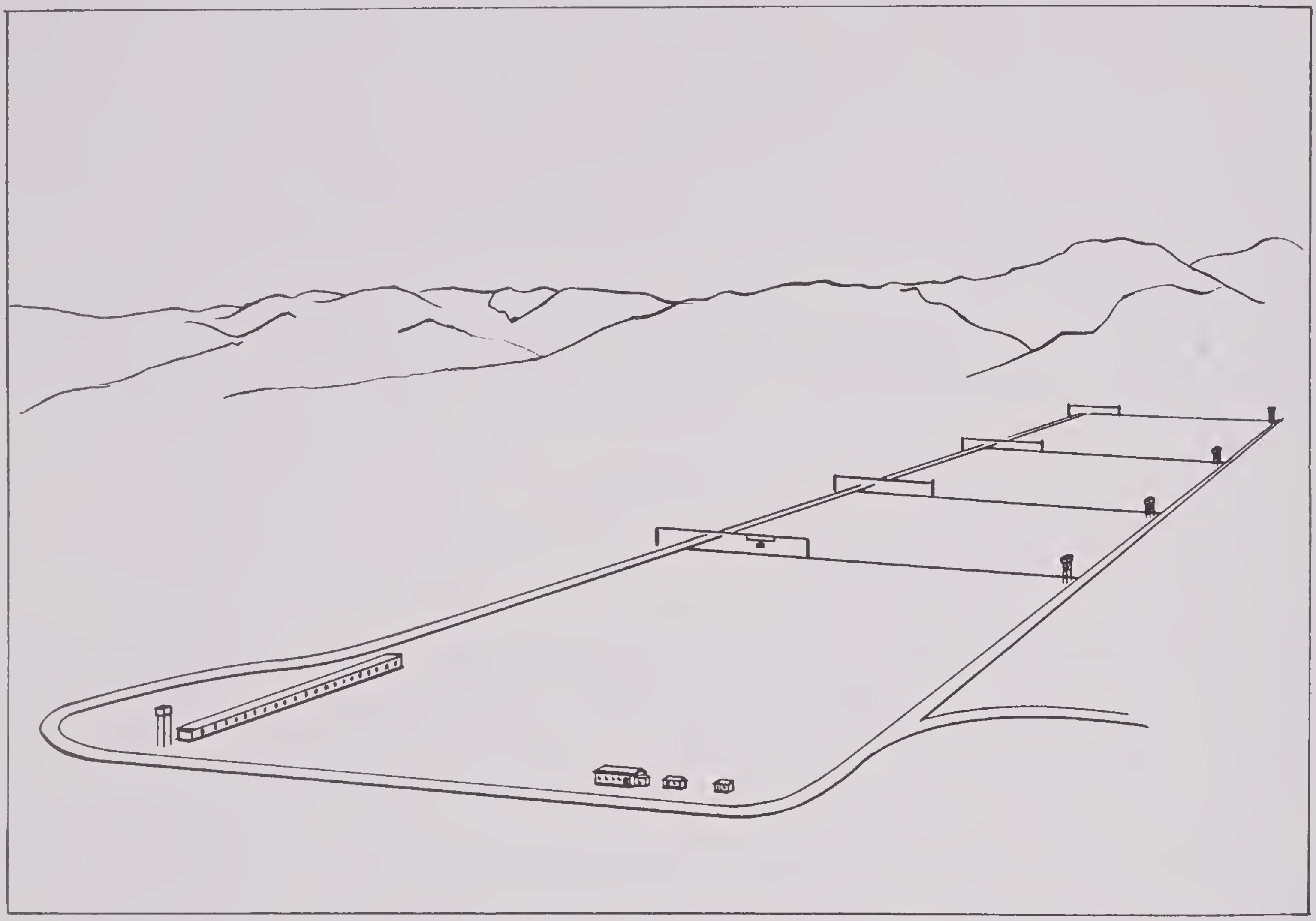

Figure 11. Perspective layout of Inyokern range.

Equipment for Study of Wave Forms

In the pure research on shock-wave amplitudes and wave forms other types of microphone such as a piezoelectric quartz crystal sound cell were at first used in place of an FEI transmitter. In this case the sound cell and preamplifier (to convert the output to low impedance) were connected by cable directly to a single-sweep oscilloscope located in a safe flank position. The sweep was triggered by a carbon microphone situated to receive the shock wave 2 or 3 msec earlier than the recording microphone. The oscilloscope had a persistent screen and was provided with momentary spot intensification by high-voltage acceleration near the screen during the sweep interval. This permitted photography of the traces at high writing speeds.

Quantitative Field Measuring Equipment for Shock-Wave Peak Amplitudes

Most of the data on shock-wave amplitudes as a function of caliber, range, miss distance, and angular positioning of the FEI transmitter were made by means of special field-measuring equipment. This operated on the same principle as that used for the Service application of the FEI, save that provision for quantitative measurements, rather than mere classification of shots into radial miss-distance zones, had to

be made. The recording equipment, usually located in a truck at a safe flank location, was operated by frequency modulation radio link to the FEI transmitter on the pole. The N-wave electrical impulses in the frequency modulation receiver are indicative of the amplitude response of the microphone diaphragms. These were pulse-lengthened[j] in several stages so as to give slowly decaying pulses that are nearly direct current. A decay time constant of 2 seconds with suitable impedance is satisfactory for driving an Esterline-Angus recording milliammeter of short period (0.75 second for full deflection). In this way the deflection of the E.A. milliammeter measures the peak value of the first rise in the N-wave pulse. Two such measuring systems were provided, one for each of the microphone channels in the dual-microphone FEI transmitter.

The Firing Error Oscillograph

The electrical N-waves output by the discriminator of the frequency-modulation FEI field-measuring receiver were also studied with photographic oscillograms by means of a cathode-ray oscilloscope. This method is very cumbersome, however, where a great number of shock-wave records must be taken unless specially designed equipment for the purpose is constructed. It has the great advantage nevertheless of avoiding the necessity for pulse lengthening with its attendant uncertainties as to accuracy, and for this reason early in 1945 work was started on the design and construction of a *firing error oscillograph* [FEO][5] with the idea of using this method exclusively for quantitative field measurements of FEI response. The oscillographic records from each of the two FEI channels are photographed on moving picture film in a camera especially designed for the purpose. The film is automatically set in motion by the firing of the gun so as to minimize the required amount of film when hundreds of rounds must be recorded. Auxiliary oscilloscopes are also provided for visual observation as a check in case of failure of operation, so that repeat shots can be made. The FEO was not used to a great extent as it was only completed and ready for use late in July 1945. Enough work was done with it to prove its value and operability, however.

The Firing Error Camera

The *firing error camera* [FEC][35] was designed and constructed in order to furnish a method of validation of the FEI reports as to shots in the case of actual towed flight. Its purpose is to determine photographically the actual position of each bullet relative to the target at the instant when that bullet reached the target plane.[k]

A deVry 35-mm-film camera is used with the film running at 10 frames per second driven by a synchronous motor. At a point in the mechanism near the driving sprocket, where the motion of the film is not intermittent but continuous, there are projected on the edge of the film the images of three small slits behind each of which is situated a neon light. Each of these three lights can be very briefly but intensely illuminated by a condenser discharge. One of them is to be triggered by a microphone circuit operated by the muzzle blast of the gun. A second is lighted in a similar way when the shock-wave signal, arriving at the FEI receiving station, announces that the bullet has passed the target. The purpose of the third light is to mark the instant at which the center of the camera shutter opening coincides with the center of the lens aperture. The shutter opening is made adjustable and in use is reduced to the smallest arc permitting adequate exposure.

The time interval between muzzle blast and shock-wave signal gives the time of flight of the bullet and from this the slant range can be obtained with the aid of the firing tables. At the same time the camera, provided with

[j] The electrical impulse charges a condenser (shunted with a high resistance) through a rectifying diode. The voltage on the condenser is the pulse-lengthened output and with suitable impedance transformation by a cathode-follower stage a second stage of pulse-lengthening may in its turn be driven from the first. The multistage method is necessary when the time constant of a given pulse must be increased by a very large factor.

[k] The idea of a shock-wave triggered camera for studying firing errors was proposed, and a camera whose shutter was timed by the shock wave was constructed in Section T of NDRC. The present camera merely indexes the instant of the shock-wave signal on the edge of a motion picture film on which the tracer bullets are being photographed, but the general idea is the same.

a red filter, photographs the tracer bullets and the target, and measurements of their separation on the film can be reduced to actual yards since the slant range is known. The rate of fire must be restricted during such tests so that only one tracer will be visible in the field of the camera at a time. Provision of a wide field finder telescope attached to the camera is to

FIGURE 12. Firing-error camera.

facilitate tracking the target by hand so that its image shall remain near the center of the field. When the developed film is examined, it becomes possible to ascertain, from measurements of the exact position on the film of the image formed by the shock-wave triggered neon light, the precise instant when the shock-wave signal impinged on the FEI transmitter. This will in general fall at some instant intermediate in time between the exposures of two adjacent frames on the film. The relative position of tracer bullet and target will be slightly different in these two frames because of the relative motion of towed target and bullet projected on the picture plane. The relative position of these two objects at the instant of the shock-wave signal can be obtained from the above described data by a linear interpolation. It is then necessary to make a small correction because the shock-wave signal is slightly later than the instant when the bullet pierced the target plane, which is the instant at which the magnitude of the miss is sought. This correction is called the delay error. The data on the film itself, reduced to yards, plus the known velocity of the bullets, furnish all that is necessary to make this correction. The corrected relative position of bullet and target expressed in yards will then permit that round to be classified as inside (or outside) a specified bull's-eye region and this result can then be compared with the report given by the FEI receiving station. Figure 12 shows the shock-wave indexing camera.

The FEC suffers from the objection that if, as sometimes occurs, the FEI fails to report a shock-wave signal for a given bullet, that round cannot be located by the FEC. Only rounds on which the FEI furnishes reports can be located by the FEC for comparison. This implies a systematic selection of the data which may be too favorable to the FEI and in consequence the final validation of the FEI in towed flight was made to depend on the Stibitz dual photographic theodolite method rather than on the FEC.

Flight Tests for Noise Study and Mechanical Reliability

Besides the above-mentioned static firing tests, flight tests had frequently to be arranged in which the FEI transmitters were towed in flags or other targets, with or without shooting by field artillery. The purpose of such tests was to study chiefly effects of noise and other disturbances in towed flight and also to serve as checks on the mechanical operability and reliability of both FEI receivers and transmitters.

Locations of Field Tests

Much of the field testing as well as the pure research on the FEI development was conducted at Camp Irwin, about 30 miles north of Barstow, California. This was the nearest practicable location where Army ordnance could be made available. The large distance coupled with the difficulties of transportation and of arranging for cooperation with several branches of the

Services at once (Artillery for shooting, Air Forces for towing, etc.) constituted one of the most difficult and time-consuming features of the work. Towing facilities were usually furnished by March Field near Riverside, California. It was usual practice to have one representative of the contract in the tow plane to communicate by radio with the others on the ground at the receiving station.

Only very small (caliber .30) experimental firing could be done at a small range situated in the outskirts of Pasadena, a few miles from the California Institute of Technology. No quantitative results of importance could therefore be obtained in this location, only qualitative checks of operability.

A considerable amount of testing work and demonstrations to the Armed Forces had to be carried out at very distant points such as Camp Davis, N. C. (for the Antiaircraft Artillery during the earlier phases of the work); Dam Neck, Va. (for the Navy); Ft. Meyers, Fla. (for the Air Forces during the earlier phases). Later a representative of the CIT contract was maintained over a period of several months at Laredo, Texas, to organize tests for the Air Forces. Representatives also spent an aggregate of several weeks at Ft. Bliss, Texas, where the camera validation tests of the FEI scoring were held.

2.5 SUMMARY OF DEVELOPMENT

2.5.1 General Design Considerations Imposed by Physical and Military Requirements

The Telemetering Problem

The acoustic FEI must be situated in the airborne target and must transmit its information regarding the intensity of the shock-wave signals, and hence the proximity of the shot, to a location near the gunner or the instructor. In order to do this with a radio link, the variations in the intensity of the received radio signals (due to varying transmission distance and other conditions) must in no way affect the quantitative significance of the information regarding the bullets. This problem in telemetering was solved by the use of frequency modulation. The earliest type of FEI used in successful field tests with towed targets consisted of a single condenser microphone connected with its variable capacity as part of the tank circuit of a small one-tube r-f transmitter. An f-m receiver placed near the gun detected the radio signals and converted the FM into brief audio-voltage pulses proportional to the response of the microphone. These pulses were suitably amplified and lengthened to give (1) audible signals in earphones, (2) visual indications of various sorts, and (3) permanent records on recording meters. Since it is the r-f shift or excursion from the carrier value which is used to indicate the shock-wave amplitude and since, in the f-m receiver of the FEI, the amplitude of the r-f signals is maintained constant by a "limiter" for a wide range of input-signal levels, the telemetered measurement is kept independent of transmission conditions so long as the signal level is sufficient to saturate the limiter.

Desirability of a Dual-Microphone System

The idea of providing *two* microphones in the FEI was first suggested as a means of furnishing directional indications regarding the misses. A much more important reason for the dual system has arisen as the work progressed. The use of two microphones with their diaphragms at diametrically opposite points of the spherical case can be shown, both by theory and practice, to give a sum response which is the sum of the peak responses of the two microphones and which is practically independent of the orientation of the microphone-pair axis to the direction of the shock wave. This property is of the greatest importance for the scoring function of the FEI for it makes the sum response of the FEI independent of the aspect angle. The shock wave does not impress its N-shaped impulse on the two microphones simultaneously and to add the peak amplitudes a rather elaborate system of pulse lengthening is required. This system is preferably located at the FEI receiving station rather than in the FEI transmitter, since it is desirable to keep the transmitters simple, compact, and light. For this reason, as well as for the advantage of directional indication, it is highly desirable to transmit separately the responses of the two microphones to the FEI receiving station. Another reason for the importance of a dual-channel sys-

tem has come to light rather late in the development. This is the discovery that the *delay error* can be very effectively compensated by introducing a specific gain unbalance in the two channels of the receiver, provided the microphone axis in the transmitter is parallel to the direction of tow. (See below and Appendix II.[2])

The Resonant FEI and the Aperiodic FEI

The original thought was to use a microphone in which the diaphragm deflections would follow the changes in pressure with some approach to fidelity in time. This implies a diaphragm of rather high natural period with sufficient damping to give a flat frequency response over the entire range necessary for an approximately faithful delineation of the transient N wave. At the outset, however, little or nothing was known about the forms of shock waves, and the high frequencies associated with the abrupt discontinuities even at very large miss distances were not suspected. The shock wave was postulated to be a simple pulse of pressure elevation having about the transit time of the bullet (of order 1 millisecond).

Early in this empirical stage of the work the idea of utilizing microphones with highly resonant tuned diaphragms was proposed. The thought was to provide two or more such microphones modulating one and the same r-f transmitter so that by tuning the diaphragms to different audio-frequency notes the signals from the different microphones could be separately distinguished by means of electric filters at the receiving station. By installing two such microphones in a box facing in opposite directions behind appropriate port holes, it was hoped that it would be possible to determine the side of the box on which a bullet had passed, by knowing which of the two microphones had the greater response. The shock wave was to excite the microphone diaphragm just as the blow of a hammer upon a bell or a tuning fork excites sustained vibrations in these instruments. It was supposed that this exciting impulse would be short compared to one cycle of the natural frequency of the diaphragm. Sustained vibration was obtained by attaching a weight at the center and by drilling holes in the back electrode to reduce the air damping. It should be clearly understood that this is a radically different scheme from the first mentioned one of using a microphone whose deflection duplicates the pressure changes in the shock wave and whose motion ceases immediately thereafter. These two different systems are called respectively the *resonant* FEI and the *aperiodic* FEI.

A very considerable amount of experimental work and field testing revealed that when resonant diaphragms, having a Q between 50 and 100 and natural frequencies of 1,600 and 2,400 c, respectively, were used, very peculiar response patterns were obtained. The response was not always a monotonically decreasing function with increasing miss distance and the peculiarities were dependent also on the caliber. Both individual and sum response patterns were very irregular in shape. In one design having a cylindrical case in which the diaphragms were not flush with the ports at the ends but communicated with the external air through a canal about 1 in. in diameter and 3/4 in. deep, the response could be almost completely suppressed by changes in the geometry of this canal. The canal was formed by inserting a sponge-rubber washer to fill the clearance between the case and the face of the microphone frame so that the sound entered through the hole in the washer. With this sponge rubber in place, normal response was obtained but upon its removal, so as to leave a large internal annular space around the entry port, response was almost completely suppressed. These effects and others led to the suspicion that the ballistic shock wave must have more sharply defined periods associated with its wave form than at first supposed. After fundamental research had revealed the N-shaped shock-wave pressure profile and its variation in period with miss distance, theoretical calculations as to the effect of such a transient on vibrating systems such as the high-Q diaphragms, led to the prediction of null response points at definite miss distances for each caliber and diaphragm frequency. These null response nodes were then experimentally verified by actual shooting. The theoretical solutions for the response of high-Q diaphragms to N-wave transients were also checked in the laboratory by means of the *electrostatic microphone tester* used in conjunction with an elec-

tronic circuit especially designed to generate electric N-wave transients of adjustable period which could be applied to the high-Q condenser microphones as an electrostatic driving force. The destructive interference at the critical null-response periods of the N wave could be clearly observed on the oscilloscope screen. It became evident that the curve of response of the resonant diaphragms as a function of miss distance exhibited nodes and loops so that to a given response level there might correspond three or even more different miss distances. Such an ambiguity is obviously very undesirable in scoring gunners, especially when it is recalled that in towed flight the doppler change in shock-wave period would greatly increase the complexity of this situation.

For these reasons, early in 1944 intensive work was started on the development of the aperiodic type of FEI, which has become the final design. For the reasons we have outlined above, this requires two distinct r-f channels between transmitter and receiver, one for each microphone.

The "Noise" Problem and Its Treatment in the Aperiodic FEI System

At the same time it was decided to take advantage of the very high audio frequencies present in the ballistic shock wave as a result of the sharp discontinuities in the wave form, to obtain improved freedom from so-called "noise" disturbances. It was not certain at the time that insertion of a filter in the receiver to cut off low frequencies would improve the signal-to-noise ratio. It was merely felt that the two extremely sharp discontinuities in the N-wave profile constituted something so radically different from ordinary sounds that possibility of such an improvement seemed a good gamble. The peak amplitudes in the N-wave discontinuities (i.e., the pressure steps) appeared to be the most desirable characteristic of the profile to use as a measure of the miss distance, and oscillograms taken in static firing indicated surprisingly good shot-to-shot reproducibility of these pressure-step amplitudes. One reason why noise elimination by restriction to higher audio frequencies seemed promising was that a comparison between even the 1,600- and 2,400-c resonant microphones frequently seemed to show a favorable reduction in signal-to-noise ratio for the higher frequency. It should be explained that the sources of noise in the FEI are far from being entirely acoustic sounds reaching the microphone by air waves. There seemed strong reason to believe that mechanical vibration of the resonant microphones (with their weight-loaded diaphragms) from the flapping of the towed target, exerted inertia forces on these diaphragms. For this reason, extremely soft shock mounting of the microphones and their supporting structures had to be provided in the resonant system. In the aperiodic system the insertion of an audio filter cutting off frequencies below 4,000 c has produced a very great improvement in the signal-to-noise ratio and also has permitted complete elimination of the shock mounting, a fact which indicates that a large contribution to the noise difficulty did indeed come from the mechanical vibration of the microphones. Other possible sources of noise interference in the low-frequency range may have been flapping of the radio antenna with consequent fluctuations in capacity which reacted upon the r-f circuits to give frequency modulations in the low audio frequencies. To avoid this a shielded *master oscillator power amplifier* [MOPA] transmitter was developed in which changes in antenna capacity and loading could react on the frequency-determining r-f oscillator to a minimum degree. (Crystal frequency control was not readily feasible since, to keep the transmitter simple, the condenser microphone capacities were shunted across the oscillator tank circuit to give the frequency modulations.)

Sum-Response Zones and Difference-Response Lobes

It was found desirable at an early stage to utilize the separate responses of the two microphones at the receiving station in the following way. Pulse-lengthened signals proportional to these responses were electrically added to form what is known as the sum response which is taken as a measure of the miss distance. The difference between the two microphone signals or some other indication as to which of the two was the greater, was taken as an indication of

the side of the transmitter on which the bullet passed. In the final Model XI-A the receiver circuits provide two directionality-indicating channels corresponding to the two microphones in the transmitter. The coupling is such that a signal appears at the output only in that channel which receives the earlier of the two signals, that from the other channel being completely blocked. The signal which does appear is a measure of the response of that microphone alone.

Adjustable thresholds are provided in the receiver in such a way that the sum signal is, according to its intensity, routed into one or more of three different sum channels. A threshold is also set below which the directionality signal produces no effect (to avoid spurious signals from accidental low-level disturbances). Choice of these thresholds therefore delineates in the target plane certain areas around the transmitter which in the aperiodic type are, for the sum response, substantially concentric circular zones. Ideally the passage of a bullet in such a zone generates a signal capable of surmounting a given threshold in the receiver, and therefore excites a recording mechanism to register the event. The directional-response threshold defines an area in the target plane on one side of the transmitter known as the *directional-response lobe* or *difference-response lobe*. Passage of shots within the boundary of this area will be recorded as a miss on that side of the transmitter. It is desirable to minimize as much as possible the variation in the dimensions of these lobes as the aspect angle of the transmitter changes relative to the direction of shooting.

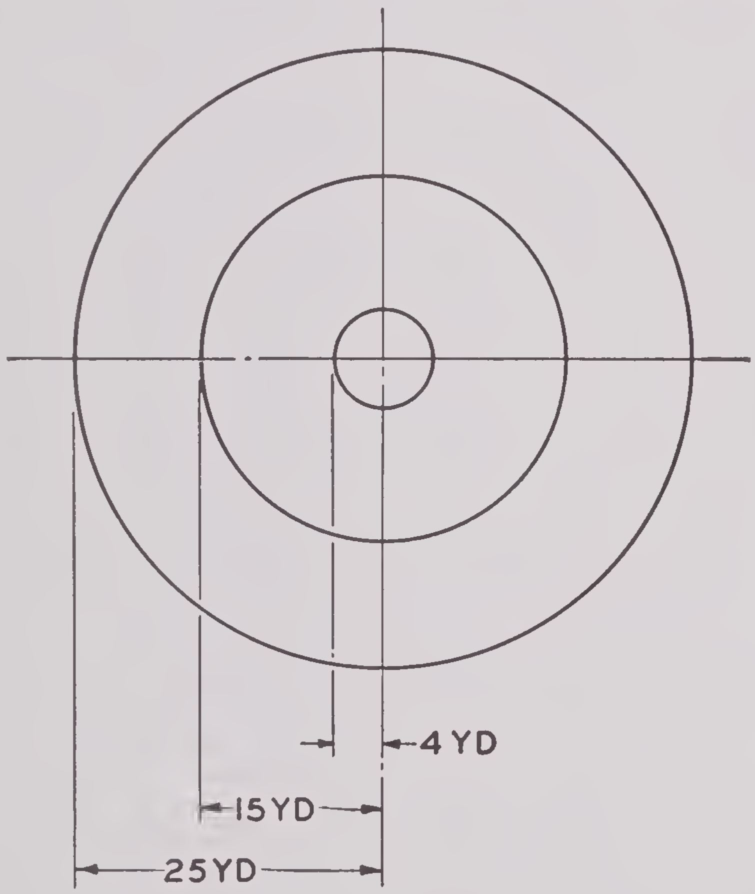

Figure 13. Radial miss-distance zones.

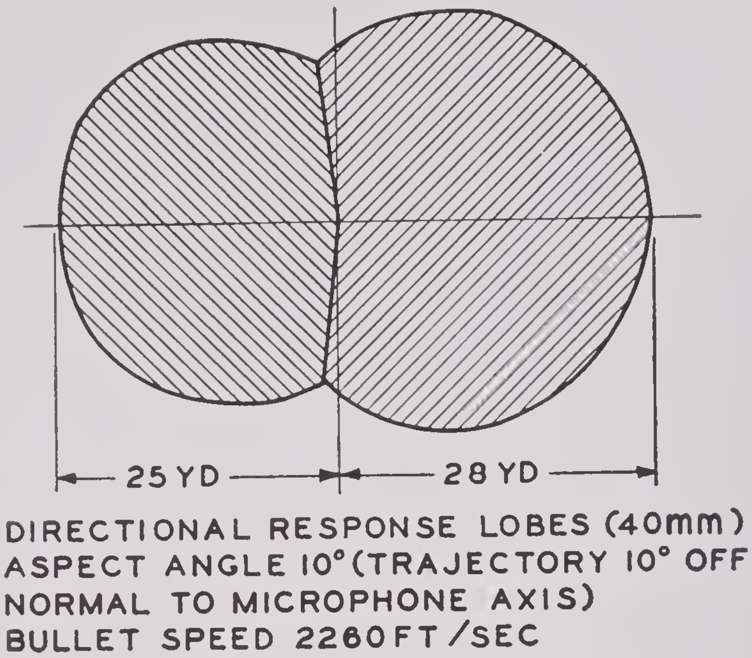

Figure 14. Directional-response lobes.

Figures 13 and 14 show an example of the zones and lobes for 40-mm fire. The unbalance in the areas of the lobes for a 10-degree aspect angle can be seen. In Appendix II[2] a complete analysis of such distortions of pattern is given.

2.5.2 Defects of the Aperiodic FEI

Listed are the sources and types of error or defect which are to be minimized or avoided in the aperiodic FEI, here summarized before a description of the design itself is given.

1. Noise. By this meant all forms of spurious excitation of the FEI system from sources other than ballistic shock waves such as wind noise, flag or sleeve flapping, excitation of the microphone diaphragms by mechanical vibration, transmitter-antenna flap producing spurious frequency modulation, interference from other radar wave, static, and gasoline-engine ignition.

2. Instability of transmitter carrier frequency.

3. Doppler effect errors. These will be present only in a system whose response is dependent on the period T' of the shock wave.

4. Delay errors. By this is meant the error which comes from the time delay between the instant of the piercing of the imaginary target plane by the bullet and the later instant of arrival of the shock wave at the microphone. Since the target containing the microphone is in motion through the air the miss distance indicated by the system will apply to the later of these two instants though it is the earlier of the two for which the information is desired. The dominant factor controlling the magnitude of this error is the ratio of the velocity of the target to the velocity of sound. (See Appendix II.[2])

5. Aspect angle errors coming from the varying aspect angles at which the microphones are presented to the shock waves for different directions of towing and shooting.

6. Unit-to-unit reproducibility of microphones and transmitters as to acoustic sensitivity.

7. Round-to-round reproducibility of the shock waves themselves.

8. Errors of receiver response.

9. Insufficient radio-signal strength limiting operating distance from transmitter to receiver.

2.5.3 Measures to Remedy Aperiodic FEI Defects

The following measures were taken to surmount, eliminate, or avoid each of the difficulties mentioned in Section 2.5.2.

1. Noise. The design of the aperiodic microphone (to be described presently) coupled with the use of an audio filter in the receiving station, has made it possible greatly to attenuate audio frequencies below 4,000 c while permitting the peak amplitudes of the shock waves to be faithfully transmitted with much less attenuation. The insertion of a band-pass filter in the circuit improves the signal-to-noise ratio by a factor 9 at 225 mph towing speed and by a factor 12 at 150 mph. By using the filter with speeds up to 225 mph, the peak-signal level for .50 caliber at 20 yd miss distance is more than 10 db above the noise, while for 40 mm this statement applies out to 40 yd miss distance.[26a] This has effectively eliminated all forms of acoustic and vibrational noise interference even as compared to shock-wave signals for the largest target zones requested. Frequency-shift noise from antenna flap has been corrected by the use of a shielded MOPA type of transmitter. Noise from outside interference has been suppressed by improvements in signal strength and in the antenna design of both receiver and transmitter. Interference from ignition systems especially in air-to-air applications is still a serious problem for individual study on each ship, for which relatively obvious solutions have been found.

2. Instability of transmitter frequency has been effectively solved by the shielded MOPA transmitter design.

3. Doppler effect errors are suppressed by the design of the aperiodic system with its special audio filter which makes the response independent of shock-wave period, T', to the required degree of accuracy for periods of 0.3 to 1.5 milliseconds.

4. The delay error can be eliminated to the first order, for the case of an aperiodic transmitter when and only when the microphone axis is parallel to the direction of tow. This is accomplished by an appropriate unbalancing of the responses of the two channels through gain adjustments in the receiver, the amount of such unbalance being dependent on towing speed. The towing speed, however, must not be too large a fraction of sonic velocity (250 mph) to prevent second-order delay errors from becoming important. This is probably the most serious limitation. The delay error if uncorrected makes the FEI transmitter less sensitive to shots placed behind the moving target than it is to those placed ahead. The zones of sum response without delay-error correction form a target which is somewhat decentered in the forward direction. An analysis of delay error and its correction is given in Appendix II.[2]

5. Aspect angle errors as regards sum response have been almost completely eliminated by the use of two aperiodic microphones mounted at opposite points of a rigid spherical encasement with their diaphragms nearly flush with the outer surface. The diffraction of the shock waves around this obstacle can be shown from theoretical acoustics to have such properties that the sum of the responses of the two microphones is almost completely independent

of their orientation. Thus for the purpose of scoring radial miss distance, the aspect angle error is practically negligible. This does not apply to directional indication however.

The apex angle of the shock-wave cone places definite limits on the aspect angles over which directional indication is reliable. Beyond this range, directionality will be indicated in reverse sense. The upper three figures in Figure 15 illustrate the geometry which controls these limits. Call this the reliable range of aspect

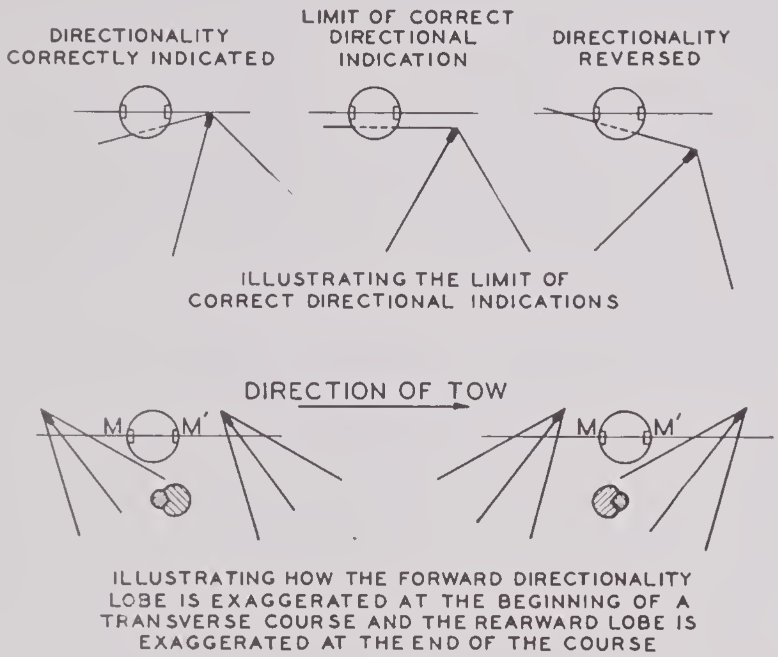

FIGURE 15. Limits of correct directionality and changes in lobe size with aspect angle.

angles, i.e., bullet trajectories falling roughly not more than 30 degrees either side of the perpendicular to the microphone axis.

The dimensions of the lobes of directionality response are still unavoidably dependent upon aspect angle, even inside the reliable range. This does not mean that inside the reliable range any single report as to firing-error directionality given by the FEI is incorrect. It merely means that for the purpose of indicating whether a shot fell fore or aft of the moving target the zone of sensitivity within which any indications are given at all will be greater around the microphone which is turned toward the gun. Although every indication given as to directionality may be correct, a gunner may appear to miss (for example) more often on the lagging side, if during his shooting the lagging lobe is larger than the leading lobe, simply because no report is given for a larger fraction of his leading misses than for his lagging misses. The lower views in Figure 15 illustrate how the leading lobe predominates in the beginning half of a transverse course while the lagging lobe predominates in the later half because of change of aspect angle. To summarize, it may be said that directional indications are not misleading for the informing function but are misleading if an attempt is made to score directionality of misses statistically.

6. The problems of manufacturing production and adjustment of microphones and transmitters to give unit-to-unit reproducibility of acoustic sensitivity to within 6 or 7 per cent have been solved by a very long and painstaking experimental production study of all the steps in manufacture and by many new techniques. Complete descriptions of all these procedures, techniques, and test methods are given in Appendix IV.[4] This was one of the most difficult problems in the entire project.

7. A great deal of static-firing data has proved the shot-to-shot reproducibility of shock-wave transmission to be better than expected (of the order of 6 or 7 per cent) and adequate for the present purpose. This is a fortunate peculiarity which comes presumably from the very large amplitudes of ballistic shock waves relative to ordinary thermal disturbances in outdoor air. The reproducibility is in all probability much poorer in towed flight because of air turbulence and other disturbances set up by the towed target. The results of validation tests in towed flight indicate that zone boundaries are much less sharply defined than in static firing. Nevertheless, much of this averages out statistically as the validation tests show (see below).

8. Receiver-response errors have been reduced to negligible proportions, provided the zone adjustments are checked at least once a month with the "E" checking equipment. In the case of airplane receivers subject to vibration more frequent checking is recommended.

9. Much attention has been given to antenna design and matching problems, both in case of receiver and transmitter, to give optimum r-f transmission distance. For ground-to-air fire, where greater distances are needed than in the air-to-air case, special receiving antennas have been designed with parasitic elements which increase the reception in the desired direction.

2.5.4 The Aperiodic FEI Briefly Described

A more complete description of the aperiodic FEI with technical information will be given in Section 2.6. The brief description here is merely for a clear understanding of the components of the device and the functions they perform. There are two main components, a transmitter located in the airborne target and a receiver, usually near the gun. Transmitter and receiver are linked by two radio carrier frequencies (e.g., 55.5 and 56.75 mc).

The Aperiodic FEI Transmitter

The transmitter, located in the airborne target, has already been pictured in Figures 1 and 2. Its spherical case is provided with two opposite openings from which the aperiodic microphones face with their diaphragms nearly flush with the surface. Protecting screens cover the openings. The diaphragms deflect in response to the shock waves from the bullets, the response depending on the obliquity with which the waves impinge. The sum of the peak deflections is, however, substantially independent of this obliquity and depends only on the distance from the bullet trajectory. Each of the condenser microphones controls the frequency of a radio-oscillator circuit so that the shift from the undisturbed frequency is a measure of the diaphragm deflection. Each microphone thus frequency-modulates a separate channel of communication between the transmitter and its receiving station. The two transmitters are operated by batteries running 2 to 4 hours on one charge.

FIGURE 16. Model XI-A receiving station.

THE FEI RECEIVING STATION

A picture of the receiving station, Model XI-A, is shown in Figure 16. This station consists of two distinct f-m receivers each of which must be tuned to the corresponding microphone channel in the transmitter. Once tuned, however, automatic frequency control [AFC] is provided to maintain it. The two f-m receivers (on the right-hand drawers in Figure 16) convert the shock-wave signals into electric voltage impulses which are measures of the peak amplitudes in the discontinuities of the N-shaped profiles. The audio section of the receiver (the left in Figure 16) contains the scoring circuits which sum the signals from the two microphones, classify this sum signal into the appropriate zoning channels, according to its intensity, and generate appropriate output pulses to drive counters or a tape recorder indicating the position of the shot in the radial zone of the target. The audio section also contains two channels to indicate on which side of the transmitter the shot was placed according to which microphone was excited first. This is indicated by impulses which may actuate either dial counters or a recording tape.

The receiver requires 110-v 60-c power to run it. For aircraft applications, therefore, where the primary power supply is 24-v direct current, appropriate inverters must be available. For this purpose a 0.75-kva 115-v 400-c inverter running on 24-v direct current has been used with very satisfactory results.

TAPE RECORDER

The electrographic tape recorder is shown in Figure 17. A motor-driven roller propels 1 in. wide, damp electrographic recording paper at a rate of approximately 1 in. per second. The paper feeds off a 200-ft spool, and the records are made by electrolytic action of 7 pens riding on the paper which is ejected through the front.

FIGURE 17. Electrographic tape recorder.

The pens are of platinum supported by steel leaf springs. The recording paper must remain moist in order for the electrolytic action to take place. The platinum tips make no mark until a current pulse passes through the pen and paper into the metal roller. The dots on the paper show instantaneously which zones were excited, thus indicating both the miss distance and directionality of each round which comes within the response pattern.

Two of the pens are brought to outside terminals as spares. These are often useful to record on the tape the instant when either of two guns is fired. The signal comes from microphones placed near the muzzles or by set-back switches operating on the gun recoil. This makes identification of the marks on the tape

much easier and gives an independent record each time a shot is fired even though the miss is too great to actuate the FEI. By comparison of such records with the FEI record the time of flight of the bullet can be obtained and the range is thus easy to ascertain.

The advantage of the tape recorder is that it gives a complete recorded history, round-by-round, of the errors of fire. The counters merely give, at any instant, totals of the number of rounds in each zone or directionality lobe since the counter was reset. Unless records are being continually jotted down from the counters by a very agile observer, information is lost as to the order in which the misses occurred or as to whether there was a tendency to lead at the start and lag at the end, etc. For scoring purposes, however, the counters alone are probably adequate although a dial counter has not as yet been developed whose mechanical action is as positive and as free from trouble and the need of servicing as is the electrolytic action of the recorder.

Counter Chassis

A counter assembly can be connected to the recorder output of the receiver. This assembly contains five dial impulse counters each of which

Figure 18. Dial counter assembly.

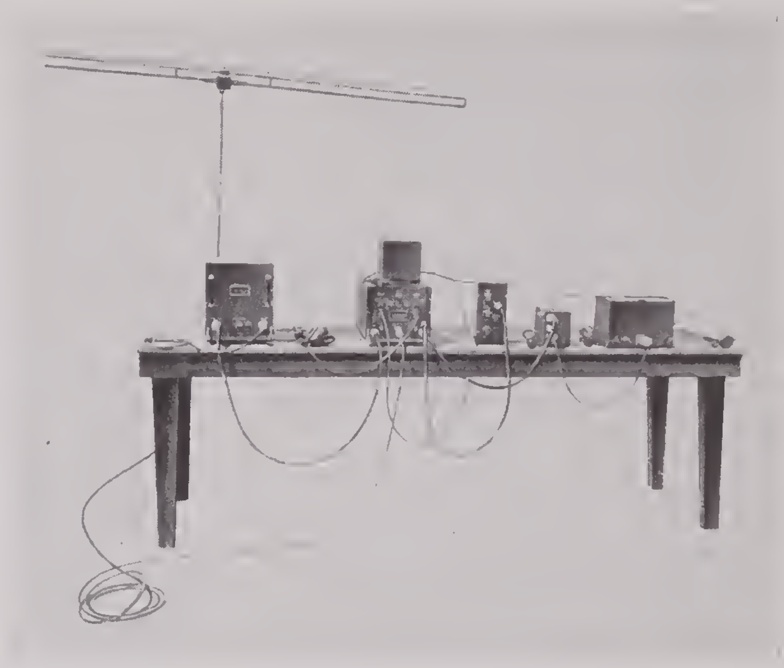

Figure 19. Photograph of complete receiving station at Ft. Bliss.

totalize the impulses in its channel, giving records of three miss-distance zones and two directionality lobes. Each counter has two indicator hands which can thus totalize 6,000 counts without resetting. The dials counting the number of rounds falling in the three radial miss-distance zones give a measure of the gunner's marksmanship.

The dial readings counting the number of rounds falling in the directionality (lead or lag) lobes have to be interpreted with care since, as explained before (see Section 2.5.3) the sizes of these lobes vary with the aspect angle of the transmitter relative to the trajectory, so that while no single directionality indication may be incorrect the trend of a gunner as to direction of miss may be misleading.

Figure 18 shows the counter assembly. The present FEI receiving station will not drive counter and tape recorder simultaneously, but either can be plugged into the receiver.

For details regarding the dial counters see Section 2.6.6.

General Appearance of the Receiving Station

Figure 19 shows an FEI receiving station set up for work in the field at Ft. Bliss, Texas. In this picture there appear the power supply, the receiver proper (Model XI instead of XI-A), the tape recorder, a small special chassis providing informing lights without counters, and

a special amplifier chassis. The latter amplifies the output of carbon microphones set up near the gun muzzles to furnish on the tape recorder the occurrence of each muzzle blast. The antenna, in this case of the directional (parasitic) type, also appears in this photograph.

2.5.5 Validation Tests of the FEI in Towed Flight by Means of Cameras

The aperiodic FEI has passed ground-to-air validation tests for its accuracy in reporting radial miss distance when used in towed flight mounted in a flag target. The tests were conducted at Ft. Bliss, Texas, during May and June of 1945. The placement of the shots relative to the target was observed with the *Stibitz dual photographic theodolite* [SPT] and an FEC developed especially for the purpose. This latter has been described in Section 2.4.2 and pictured in Figure 12. On the FEC film the instant of arrival of the shock-wave signal at the trans-

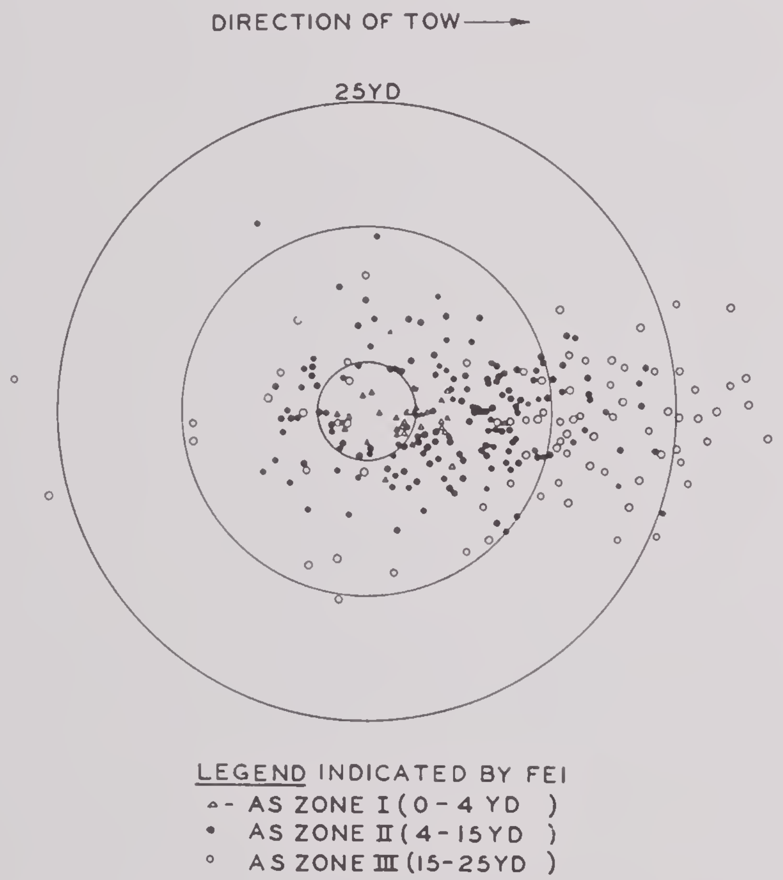

FIGURE 20. Combined plot of firing of May 21 and flak analysis firing of May 28–June 1. FEI versus FEC. Location: Ft. Bliss, Dona Ana Range; caliber: 40 mm; number of rounds plotted: 269.

mitter is indexed to determine when the tracer bullet pierces the target plane. Plots were made in which the actual position of each shot in the target plane as ascertained by the camera was plotted to scale. A report on the same shots by the aperiodic FEI as to the nominal miss-distance zone in which each shot fell (i.e., 0 to 4 yd, 4 to 15 yd, or 15 to 25 yd for 40-mm fire) was indicated by a circle, dot, or triangle at the point in question. The circular nominal zone boundaries were drawn to scale on these plots for comparison with the FEI report. Three plots of this type are shown in Figures 20, 21, and 22. It will be noted that a certain number of shots actually falling outside a given zone boundary

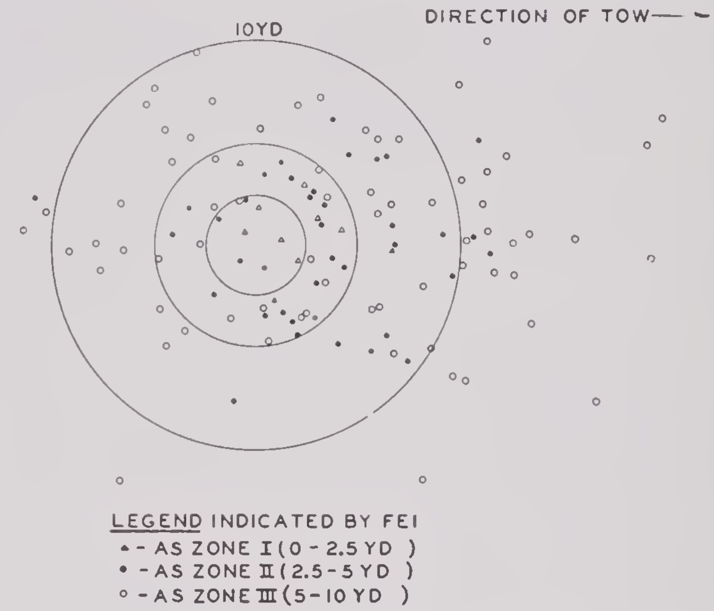

FIGURE 21. Correlation of FEI with FEC. Location: Ft. Bliss, Hueco Range, June 4–5, 1945; caliber: .50; number of rounds plotted: 120.

are recorded as inside and vice versa. This lack of sharp definition of the zone boundaries is much more in evidence for the case of towed flight than for the case of static firing, for reasons discussed in Appendix II[2] under the heading of "Errors from Noise." Figure 23 is a shot diagram taken in static fire to illustrate this point by comparison with Figures 20, 21, and 22. (For a more complete account of such static shot-response patterns see OSRD 4664.[28]) Obviously less weight should be attached to a wrong report by the FEI as to radial zone if the shot is just outside the zone boundary but close thereto than if it is farther away. Furthermore, errors in reporting miss distance are less serious for large miss distances than for closer hits. Therefore some quantitative procedure for scoring the FEI against the camera must be worked out if a single figure is to be assigned as a measure of the accuracy of the FEI. This procedure is described now. A more complete account and analysis of the camera-validation tests has been given in OSRD 5553.[32]

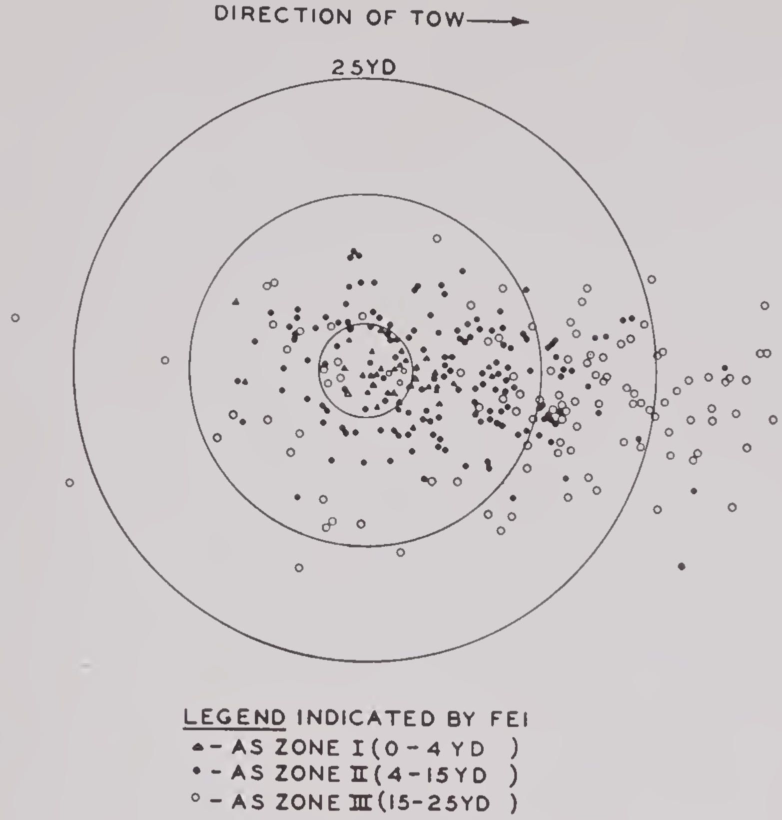

FIGURE 22. Combined plot of firing of May 21 and flak analysis firing of May 28–June 1. FEI versus Stibitz. Location: Ft. Bliss, Dona Ana Range; caliber: 40 mm; number of rounds plotted: 295.

Method of Computing Scores and FEI "Accuracy" by Harmonic Mean Miss Distance

The numbers of rounds reported by the SPT in each concentric radial zone (as, for example, Zone 2 between radii 4 and 15 yd) are tabulated in Table 4 for the three zones and outside Zone 3. In the SPT column the 170 shots in this latter category were simply those observed to fall outside the 25-yd radius. All of the 537 rounds discussed were therefore located by the SPT camera. The 193 rounds in the FEI column is the difference between the total rounds and the sum reported by the FEI in its three zones. There is also tabulated under the label *Target Scores* the number of rounds falling inside the three circular areas of radii 4 yd, 15 yd, and 25 yd, respectively, by the FEI and by the SPT for comparison. The tabulations are expressed both as hits and as per cents of the 537 total rounds photographed by the SPT. It will be noted that there is satisfactory agreement between the per cent scores as given by the FEI and by the validating SPT camera.

In order to obtain a single figure of merit with which to express the accuracy of the FEI in reporting miss distance, the harmonic mean miss distances from the FEI zone reports and from the SPT zone counts for comparison were computed. To do this the number of shots reported in each zone by either device is divided by the mean radius of that zone, the three quotients are added and the sum is divided by the total number of shots. The reciprocal of this result is the harmonic mean miss distance.

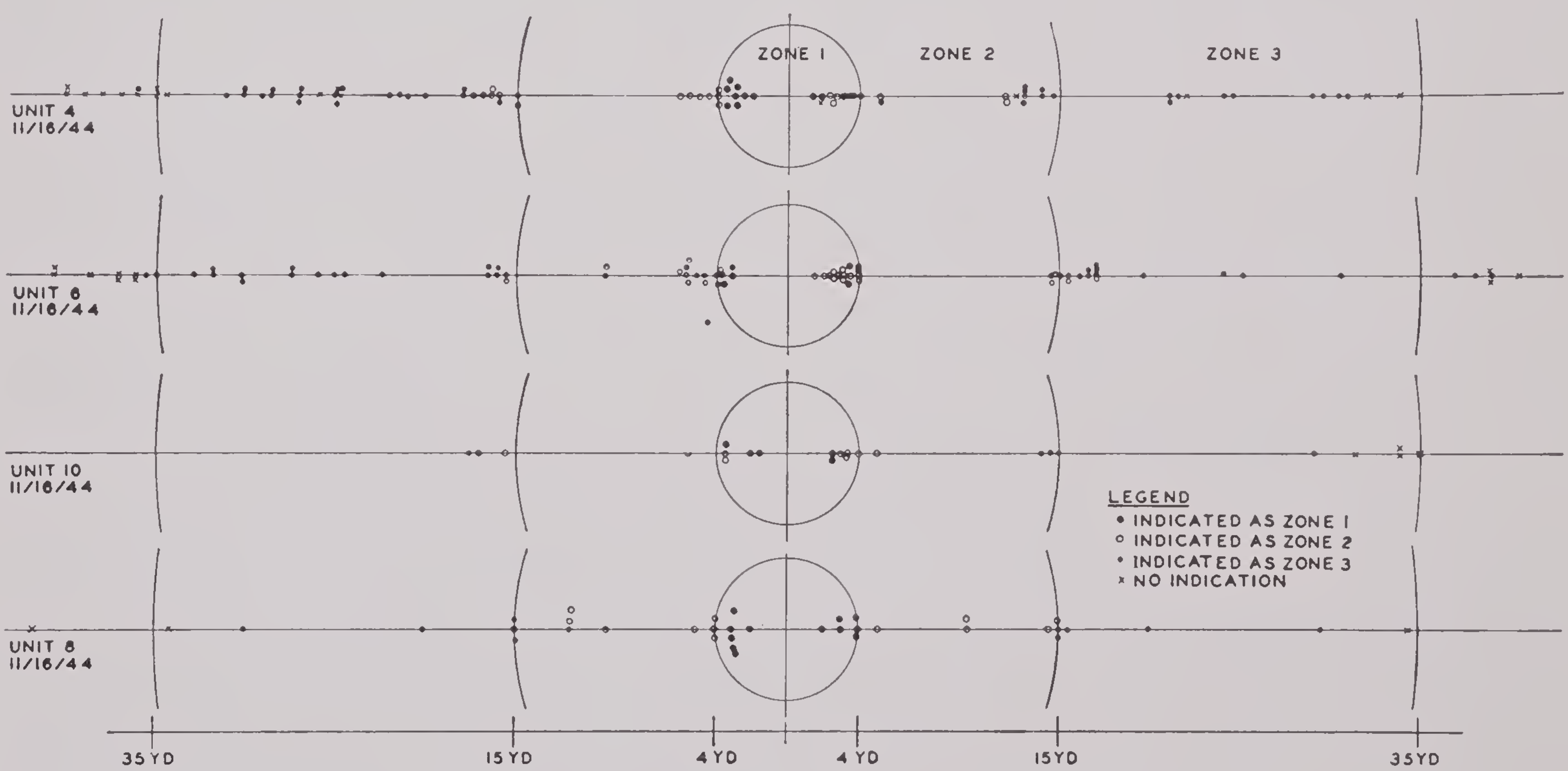

FIGURE 23. Shot pattern in static fire, 40 mm, Camp Irwin.

TABLE 4. Scoring data, Ft. Bliss, 40 mm, May 21 and May 28 to June 1, 1945

	Zone Scores FEI		SPT	
	No. of hits	Score %	No. of hits	Score %
Zone 1 : 0-4 yd	45	8.4	45	8.4
2 : 4-15	169	31.5	205	38.2
3 : 15-26	130	24.2	117	21.7
Outside 3 : 25-	193	35.9	170	31.7
Total	537		537	

Harmonic mean miss: FEI 11.49 yd; SPT 10.77 yd.
Per cent disagreement: 7%

	Target Scores FEI		SPT	
	No. of hits	Score %	No. of hits	Score %
0-4 yd	45	8.4	45	8.4
0-15	214	39.9	250	46.6
0-25	344	64.1	367	68.3

Number of transmitters used
On the 40-mm scoring, 7 transmitters were used on five different days.
On the .50-cal. scoring, 5 transmitters were used on two different days.

Comparison of Zone Scores of FEI and SPT

It will be noted from Table 4 that the FEI reported a harmonic mean miss distance of 11.49 yd, while the SPT reported 10.77 yd. The difference, an error of 7 per cent may be taken as an expression of the accuracy of the FEI if no error whatever exists in the SPT. This method amounts to weighting the number of shots in a given zone in inverse ratio to the mean radial miss distance of the zone. This procedure is rational since, down to a certain lower limit, accuracy in reporting closer shots is more valuable and should receive greater weight. This statement is true, of course, only down to a certain lower limit of miss distance. The innermost zone (e.g., 2.5 yd for caliber .50) may be roughly identified with this lower limit. There is probably less value in discriminating between shots as to miss distances of a few feet since such differences can come from many complicated ballistic causes not connected with marksmanship. It is also reasonable as being quite closely related to what the FEI actually measures, namely the amplitudes of the shock waves which are nearly in inverse proportion to miss distance.

Comparison of Target Scores of FEI and SPT

If examination is made of target scores it is seen that the largest circular target area of 25-yd radius was of such size as to permit a score of over 60 per cent hits. For rating gunners most reliably and economically from the point of view of minimizing statistical fluctuations of score this size is the one to be preferred over the others.[30a] For this size, the absolute difference in score between the FEI and SPT was 4 per cent, an amount which is about 6 per cent of the score itself.

Probability Curves for FEI Zones

As an alternate method of indicating the performance of the FEI, there is shown in Figure 24 a plot, from the camera validation data, of

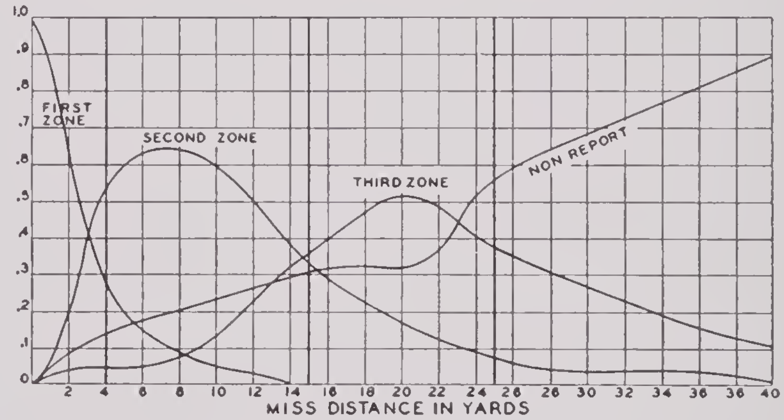

FIGURE 24. Zone-recording probability. The ordinate of each curve gives the probability that a shot at the given miss distance will be recorded as being in that zone. Location: Ft. Bliss, Dona Ana Range, May 21, May 28–June 1, 1945; caliber: 40 mm.

the probability, as a function of radial miss distance, that the FEI will report a 40-mm shot as falling in each one of the three zones. A fourth curve indicates the probability of failures to

report. The nominal boundaries of the zones are marked with heavy vertical lines.

It should be noted from this plot that the FEI may report a shot as in a given zone which was shown by the photographic theodolites to have fallen elsewhere. Also the FEI may fail to report a shot which was actually placed inside a given zone boundary according to the theodolites. These two effects have a mutually cancelling tendency, the net result being an unsharpness of the zone boundaries. It is this increased unsharpness of the zone boundaries in the case of towed flight as compared to static firing which leads to the belief that the shot-to-shot reproducibility of the shock waves as received at the microphones is considerably impaired by the turbulence of the air and other disturbances associated with towing. The results in Table 4 show that for statistical purposes of scoring, however, these effects tend to average out in a very reasonably small number of rounds, so as to leave no serious error in the score. For the number of rounds fired the uncertainty in the score so introduced by the FEI is far less than the statistical uncertainty in rating a gunner by the number of holes he could have made in a flag on the same number of total fired rounds. Unfortunately no record of the number of direct flag hits is available but it is easy to compute, from the mean density of shots recorded by the SPT inside the 4-yd radius, approximately how many holes could be expected. This is only about 8 holes, a number so small that there is, according to statistical theory, about 30 per cent chance of its being in error either way by more than $\sqrt{8}$ holes, or very nearly ± 3 holes (i.e., the standard deviation). Thus the flag score for an expenditure of the same 537 rounds would stand a 30 per cent chance of being in error by ± 35 per cent or more ($\sqrt{8}/8$) of the score itself, as compared to the error of 6 per cent of the score with the FEI.

As a final result, it may be stated from the Ft. Bliss tests that the FEI reported radial miss distance (i.e., harmonic mean value) with an error not greater than 7 per cent. This figure is based on the assumption of complete accuracy of the validating camera. This assumption is not completely true but although correction of camera errors, if it were possible, might reduce the figure of 7 per cent error in the FEI, it would probably not be a large effect because it is the squares of the standard deviations of the two methods which are additive.

The accuracy of the FEI indicated by these tests is regarded as satisfactory by the using Services. The enormous gain in the number of shots whose proximity to the target can be recorded (in comparison to the number of direct hits on flags or other material targets) is the element of greatest advantage. In the case of direct hits the number of these is so small that the statistical uncertainty as to their significance is enormously larger than the 7 per cent error of the FEI.

The FEI was used during the latter part of June 1945 by the 37th AA Brigade, Los Angeles, to determine the relative merits of different gun sights. As an index of its statistical superiority over the method of direct hits, it may be stated that in these tests, out of 103,768 rounds which were fired, 120 direct hits on the towed flags were recorded while the FEI furnished zone data on the proximity of 16,111 rounds.

For a more complete report on the camera validation tests of the FEI in towed flight, see OSRD Report 5723.[34]

2.5.6 Limitations of the FEI as Developed to Date

Limitations as to Application

The duration of the work on this project was not sufficient to permit the development of the FEI for all applications which have been suggested or requested by the Armed Forces since its inception. As developed to date, the FEI has only been studied for use in towed flag targets and in gliders for ground-to-air firing and for air-to-air (bomber-to-fighter plane) firing. In the first case the calibers studied have been caliber .50, 20 mm, and 40 mm. In the second case only caliber .50 has been studied. Work was started on the application to small radio-controlled plane models as targets (the OQ model) and it was found by test on the OQ3 that no serious interference was to be expected from the sound of the motor. Time has not permitted further work on this very promising application.

Requests and suggestions have been made for

development of the FEI for use with larger calibers such as 90 mm and at higher altitudes. It should be clearly understood that in the case of the larger caliber explosive projectiles the FEI in its present form would be suitable for indicating the shock wave from the passage of the unexploded shell past the aerial target but not suitable for indicating the burst. An FEI working on the burst would probably require a considerable amount of new fundamental research as well as development. Even for indicating the passage of 90-mm shells by shock wave with the present FEI a considerable program of static firing would be needed.

The question of calibration for high-altitude work would also call for a much extended program. To date only altitudes from sea level to about 8,000 ft (3,000 ft above Ft. Bliss, Texas) have been studied. Over this range there was not detected any significant change in calibration with altitude. Such constancy, however, cannot be guaranteed, without tests, at altitudes such as 20,000 ft.

None of the applications of the FEI to training of fighter pilots in fixed gunnery has been studied.

A naval application of the FEI to the scoring of air-to-air rocket fire was initiated in 1944. Since the rocket differs widely in many respects (geometry, speed, ballistic constant, etc.) from the projectiles already studied and since also it was to be fired forward from a plane already moving at high velocity, this study, as pointed out in Section 2.3.5, called for the construction of a special 350-ft launching rail installation with a static-firing range to permit firing the rockets from initially moving rocket-propelled carriages under correctly simulated conditions for calibrating FEI transmitters. This range has been in process of construction by the Navy at the Inyokern Naval Ordnance Testing Station, but the pressure of more urgent work has delayed it so that it was not ready for use in connection with this work.

Limitations Imposed by Physical Conditions

Besides the above-mentioned limitations, the FEI as at present developed has other limitations:

1. Weather conditions such as rain, or ice, may prevail so that a coating of water or ice forms on the microphone diaphragms. Such coatings modify the calibration so as to cause erroneous results, as laboratory tests have shown.

2. As stated above, calibration is unknown for altitudes above sea level greater than 8,000 ft.

3. The spherical transmitter must be mounted on its target or other supporting vehicle in such a way that the shock waves from all bullet trajectories to be scored, wherever they may pass, can come directly to the transmitter sphere without encountering intermediate obstacles and can sweep on all sides of the sphere with as free clearance, all around, as possible. (Narrow rods, guy wires, or stays are less serious obstacles in this respect than large, flat rigid surfaces.) Acoustic reflections from nearby surfaces must also be carefully avoided. It has been frequently suggested, for example, that the two hemispherical parts of the transmitter be divided, placing the two halves as "blisters" on the opposite sides of the fuselage of a radio-controlled plane. Such a procedure would be fatal to the scoring accuracy of the present device. A complete restudy by static fire to find the new shapes of the sum-response zones and their changes in shape with different aspect angles would be required. In all probability the results would be too complicated for practical use in the comparative scoring of marksmen.

4. Radio reception distances in the present FEI can hardly exceed four miles under the best conditions yet encountered. This distance could, of course, be extended by a redesign of the transmitter with more powerful tubes, but this would result in much shorter battery life or considerably more battery weight to be supported in the airborne target. In an application of the FEI to blast-pressure measurements from the atomic bomb (see Section 2.5.7) it was possible to support greater weight because the equipment was mounted in a parachute. Reception distances of 10 miles were thus realized. An operating time, however, of only a few minutes was required.

5. The projectile speeds must be substantially in excess of the velocity of sound as they pass the target (preferably at least 1,400 ft per second).

6. If the bullet trajectories make an angle with the microphone-pair axis differing too

greatly from 90 degrees the directional indication, as already explained, will be unreliable or even reversed.

7. Towing speeds are probably limited (chiefly by the delay error) to speeds not in excess of 250 mph. The ratio of the towing speed to the velocity of sound is the chief controlling factor here.

8. Attention is called to the discussion under Section 2.6.8. It is important to record here that any changes from the present physical design of microphone and transmitter may make it necessary to repeat the entire process of field calibrations by as extended a program of experimental static firing (see Section 2.4.2 and Appendix V[5]) as this project has already undertaken. In view of the amount of time, special field-measuring equipment, and experience that this has required, such a repetition is an important consideration not to be taken lightly. Changes, even though they promise minor improvements, must be considered with this in view.

2.5.7 Application of the FEI to the Measurement of Blast Pressure from the Atomic Bomb

Work was begun in April 1945 to utilize the FEI as an airborne pressure gauge over enemy-held territory. The purpose of the measurement was to determine the efficiency of the atomic bomb in combat by comparing amplitudes of the pressure waves with those from known amounts of TNT.

Apparatus

Transmitter. A standard FEI transmitter is used to drive a power amplifier feeding approximately 30 watts to a linear antenna. Only one half of the standard spherical unit was used. This considerable simplification of the FEI could be made in this special application because the conditions of the measurement were such that the angle of approach of the shock wave to the microphone hemisphere was known beforehand for reasons soon to become clear.

The hemispherical single microphone-transmitter unit is carried facing downward on the bottom of a cylindrical container about 36 in. long carrying the power stage and batteries. This assembly is dropped by chute from the bomber (with the microphone facing downward) at about the time the bomb itself is released. While the unit is still in the bomb bay the transmitter is operated by the airplane generators to save the battery; but as soon as it is dropped, power supply is switched to the internal batteries. These need then operate the transmitter for only a few minutes. By this means as well as by the use of much larger batteries it was possible to increase the transmission distance up to 10 miles. Before use, the batteries are kept warm by electrical heating as the altitudes for this work were considerable. The temperature and current drain are such that the output power is halved in 1½ minutes after dropping.

It turns out that the microphone sensitivity required here is the same as in regular FEI work. The microphone was therefore of standard construction except for a calibrating device consisting of a piston, operated by a time fuse, which raises the pressure in the microphone chamber behind the diaphragm by a predictable amount. The resulting signal, timed to occur very shortly before arrival of the expected blast, thus offers an overall calibration.

Receiver. The signals were received with the receivers originally manufactured for use with resonant transmitters. It was possible to use these resonant-system receivers because only one channel of information was needed. The special audio filter of the aperiodic receivers was omitted since the noise and mechanical vibration incident to towed flight were absent in this parachute application and it was desired to obtain an oscillographic record of the complete pressure wave profile, not just its discontinuities. The receivers were modified to feed a recording oscilloscope using a 3-in. blue screen tube situated in the bombing plane. Records were taken with a 16-mm, continuous motion camera. The entire system is direct-current coupled in such a way that even very slow impulses are recorded.

Performance

The airborne pressure gauges were used at an experimental explosion of 100 tons of TNT in June 1945. Excellent records were taken, in complete agreement with theoretical pressures.

No records were taken during the explosion

of July 16, 1945, at the Alamogordo Air Base, N. M., because of poor weather conditions.

Excellent pressure records were obtained over Hiroshima and Nagasaki. The estimates of "equivalent tons" of the bombs dropped on Japan are based on these records.

2.6 DESCRIPTION AND TECHNICAL INFORMATION

2.6.1 Experimental Production Program

Two facts made a rather extensive program of experimental production unavoidable. These were (1) the expendable nature of the FEI transmitter units when used in flag targets and gliders, and (2) the fact that the problem of obtaining a high degree of unit-to-unit reproducible sensitivity in the transmitters was a paramount one to be solved. A design could not be "frozen" for quantity production until all the pertinent problems had been solved and until procedure had been standardized so that all the units manufactured would meet the requirements established and a sufficient number of satisfactory units had to be adequately tested by the contractor's personnel and by the using Services. In all, some 460 aperiodic transmitters (each containing two microphones and two radio transmitters) were constructed, and, in addition, 295 single transmitter units of very special type were constructed for the Manhattan District for the study of atomic-bomb blast pressures. Beside these, a large number of experimental types were constructed earlier, before the satisfactory design was determined.

Twelve distinct models of the FEI receiving station were designed, and several were constructed to permit simultaneous experiments with them at widely separated military locations designated by the different interested Service branches. In all, about 15 receivers of the various models were constructed in this experimental production.

The experimental production was carried on under Contract OEMsr-600 on the campus at CIT.

2.6.2 The Aperiodic FEI Microphone

This all-important component, whose technical details of manufacture are more fully described in Appendix IV,[4] is shown in Figure 25. The exploded (top) view shows the five parts: the lock nut, the stretching button consisting of a threaded brass ring with insulated back

FIGURE 25. Two views of aperiodic FEI microphone (exploded and assembled).

electrode mounted on ceramic (steatite) insert, the frame, the beryllium copper diaphragm 1.6 mils thick, and the clamping ring. The diaphragm which is under high tension approaching its elastic limit is very securely held by 16 screws through the clamping ring into the frame. It is assembled under pre-stress by means of a special jig and the final tension is then adjusted by screwing the button up against it from the back to the proper degree until its natural frequency is 10,000 c. The diaphragm clears the back electrode by only 0.00098 in., this gap being determined by special machining and testing methods when the button is made as explained in detail in Appendix IV.[4] The small clearance produces very high diaphragm damping so that there is no sustention of the natural diaphragm frequency and that frequency can therefore only be determined by special methods with the electrostatic tester.[4] The gap is such that the microphone frequency-response curve is extremely flat over the range from 1,000 to 10,000 c as measured on the electrostatic tester described and discussed in Ap-

pendix IV.[4] These characteristics and their stability against temperature variations are essential to the success of the aperiodic FEI. Matching of thermal expansion coefficients has been carefully attended to. Artifical aging of the microphones by temperature cycling is an important step in their manufacture.

The active diameter of the diaphragm, defined by the inside diameter of the threaded stretching ring, is $\frac{3}{4}$ in. and this conveys an idea of the dimensional scale in Figure 25. It is an essential feature that the clamping ring be very shallow so that in the assembled unit no marked acoustic shading or interference effects are produced by this ring. Figure 26

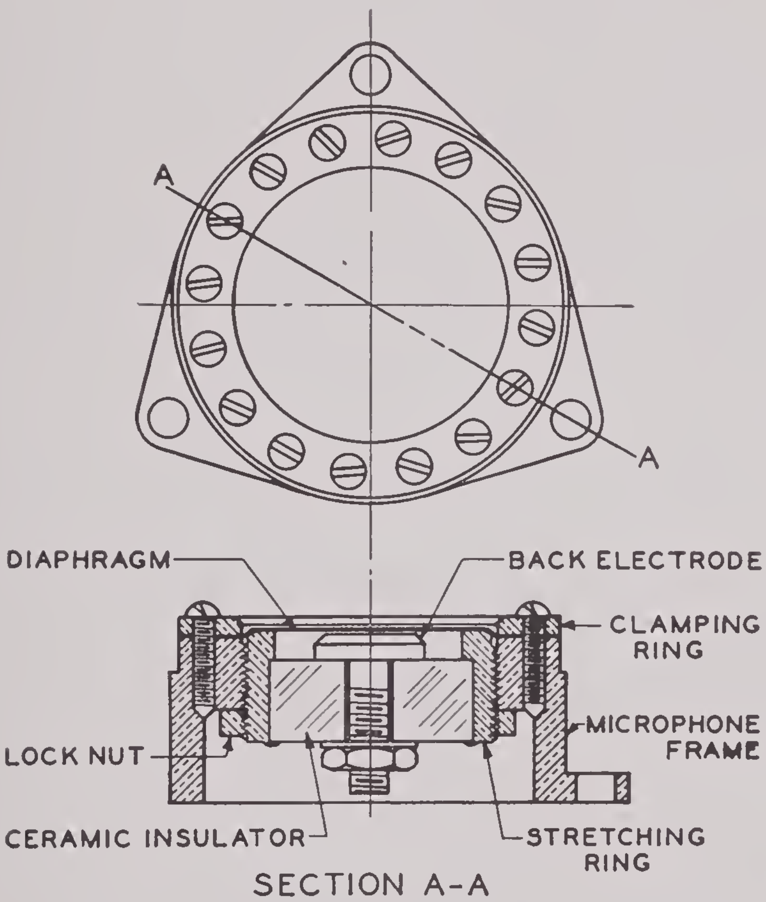

FIGURE 26. Cross section of aperiodic FEI microphone.

is a cross section through the assembled microphone and Figure 27 is a cross section through the stretching button.

The space behind the microphone diaphragm must have a vent to the outside air to equalize changes in pressure accompanying changes in altitude. The limits on the time constant of this vent are important. Two successful types of vent have been used, (1) a fine hole, a mil or so in diameter, punctured through the diaphragm very near its active periphery; (2) a fine scratch made across the profile of the

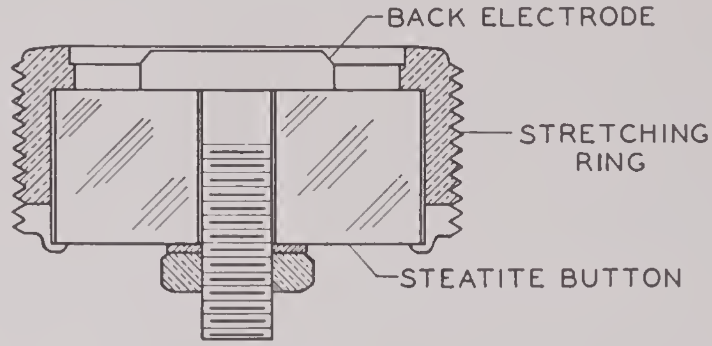

FIGURE 27. Cross section of aperiodic FEI microphone stretching button.

stretching ring where the latter contacts the back of the diaphragm. The last type of vent seems to be slightly preferable and somewhat easier to produce.

2.6.3 The Aperiodic FEI Transmitter Unit

The FEI transmitter is of the MOPA type. The microphone is mounted directly on top of the cylindrical box which shields the oscillator components so that a very short internal lead wire connects it to the frequency-determining elements of its master oscillator.[1] This disposition can be clearly seen in Figure 28 (as well as

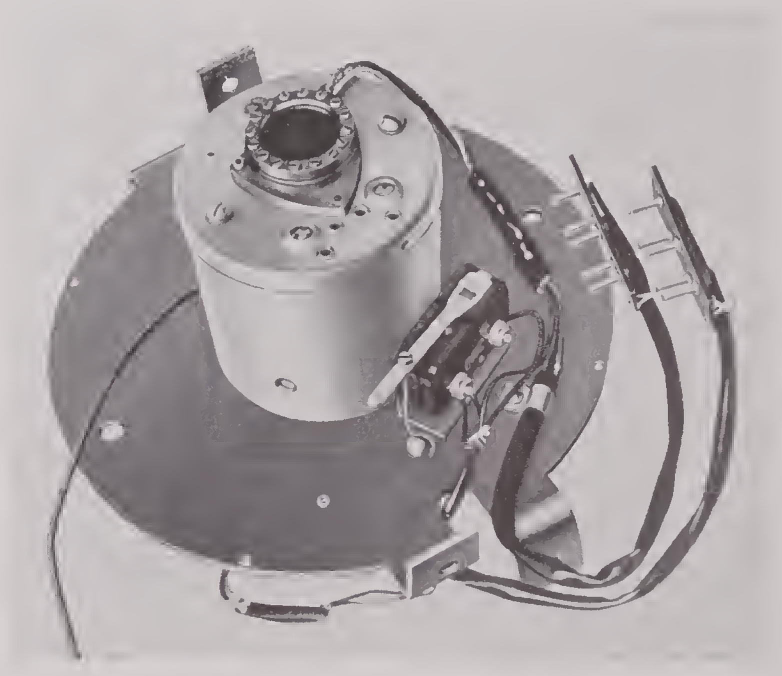

FIGURE 28. Aperiodic FEI transmitter unit with two hemispherical plastic housings removed.

in Figure 1). In Figure 28, the two plastic hemispherical shell encasements have been removed, so that one can see the auto-

[1] The substitution of a cylindrical box for the older rectangular box, to shield the r-f transmitter components inside the plastic hemispheres, is a minor improvement which has been made since Reports OSRD 4967[29] and 4968[30] were issued.

matic switch at the right which turns on the battery power supply when the target is launched. These parts are assembled on a disk-shaped Dural septum to which the hemispheres are attached. One of the assemblies consisting of the microphone and MOPA components removed from the housing, is shown in Figure 29. Two such assemblies enter the cylindrical shield from either end. When the plastic hemispheres are assembled on the central septum their outside surfaces are practically flush with the microphone diaphragms. Wire grills are attached to the hemispheres to protect the diaphragms. The mounting of the transmitter units in flags and on gliders has already been described and pictured in Figures 1 and 2.

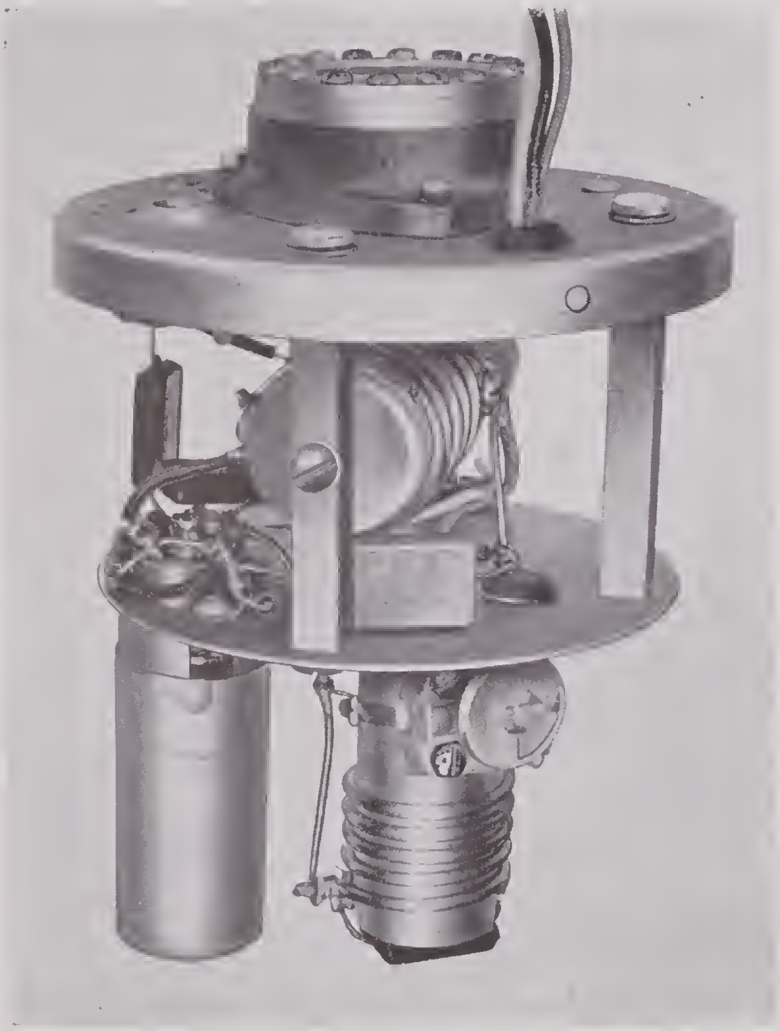

FIGURE 29. Microphone and MOPA.

Two independent end-fed half-wave antenna wires are used, one for each of the microphone transmitter units.

In Figure 30 a schematic wiring diagram of one of the FEI transmitter-microphone units is shown. The oscillator and amplifier triodes are in a single tube envelope. The inductively coupled coils L_1 and L_2 of Figure 30 are wound on a single plastic core visible in Figure 29 as the higher of the two coils. The double triode and the antenna output coil L_3 of Figure 30 are visible at the bottom of the assembly in Figure 29.

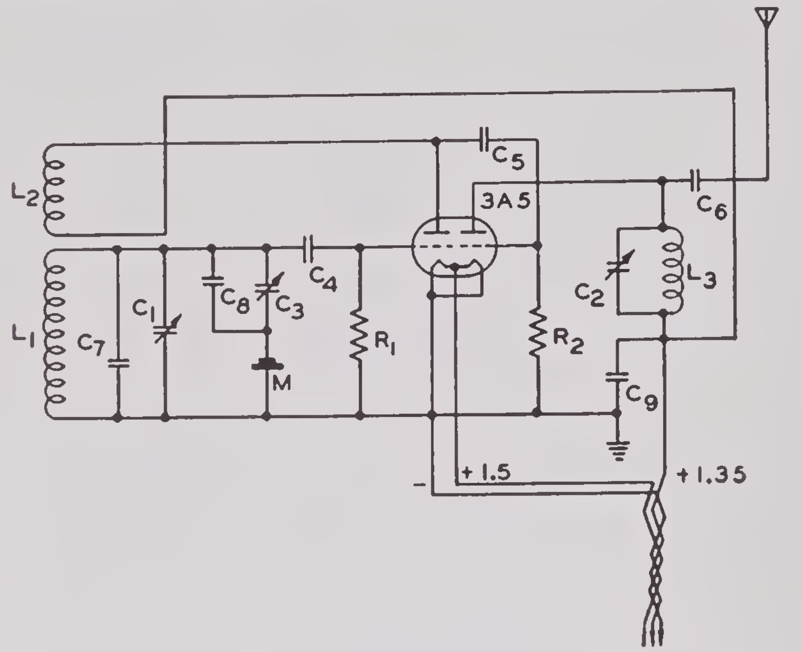

FIGURE 30. Schematic wiring diagram of FEI transmitter-microphone unit.

2.6.4 Physical Characteristics of Aperiodic FEI Microphones and Transmitters

The following list of specifications and physical characteristics is given to complete the information relative to microphone and transmitters.[33]

MICROPHONES

Diaphragm material. 1.6-mil beryllium copper shim stock rolled "3 numbers hard."

Diaphragm (natural) frequency. 10,000 c ± 300 c. [By diaphragm (natural) frequency is meant the frequency at which the diaphragm displacement will be 90 degrees out of phase with the driving force applied to the diaphragm as indicated by the electrostatic microphone tester.]

Active diaphragm diameter. $\frac{3}{4}$ in.

Diaphragm membrane tension. Approximately 115 lb per linear inch.

Diaphragm "Q." Approximately 0.8.

Electric capacity of microphone. $25 \mu\mu f \pm 5 \mu\mu f$.

Air-gap clearance. 0.00098 in. (held by special procedure with pneumatic micrometer).

Air-gap diameter: 0.375 ± 0.002 in.

Dead-air volume. 0.0275 cu in. (annular space around back electrode).

Time constant and vent and dead-air volume. Between 0.1 and 0.002 second.

Relative frequency shift. $\Delta f/f = 0.025\Delta C/C$.

Sensitivity. $\Delta C/C\Delta p$, (relative capacity change per unit change in pressure) $= 2\times10^{-6}$ per bar. Hence frequency shift $\Delta f/(f\Delta p) = 5\times10^{-8}$ per bar.

Microphone frames. Castings of special brass alloy as follows: 85 per cent copper; 5 per cent tin; 5 per cent zinc; 5 per cent lead described as QQ-B-691 Composition 2 casting brass (to match thermal-expansion coefficient of beryllium copper).

Microphone clamping rings. Retained with 16 screws and machined slightly conical to give contact on inside edge and spring-washer effect.

Temperature coefficient of sensitivity. Less than 0.015 db per degree centigrade measured between 0 C and 60 C.

Stability of resonant frequency. The resonant frequency shall not change more than 1 per cent after the microphone has been subjected to a temperature cycle from —40 C to +60 C with the microphone held for 1 hour at each extreme temperature.

TRANSMITTERS

Radio frequencies. 55.5 and 56.75 mc respectively.

Type of oscillator. Shielded MOPA.

Modulation. Frequency modulation by condenser microphone across tank circuit of oscillator.

Tube. Double triode—3A5.

Coil dimensions. L_1—4¾ turns, No. 12 wire, 5 turns per inch, ⅞-in. diameter; L_2—5⅝ turns, No. 16 wire, 5 turns per inch, ⅞-in. diameter; (coils L_1 and L_2 are interwound); L_3—4½ turns, No. 12 wire, ¾ in. long, ¾ in. diameter.

Battery supply. 1.5 and 135 v. One Signal Corps BA-49 iron-clad battery is used for each side of the transmitter in the flag mount. Four batteries are used in the glider mount to increase the operating time.

2.6.5 The Aperiodic FEI Receiving Station Model XI-A[37]

Model XI-A, the final model of aperiodic FEI receiver defined for manufacturing production is shown in Figure 31. It consists of three separate chassis assemblies fitting as drawers in a single supporting frame.

This three-drawer model is a minor improvement over the more compact single-chassis Model XI.[29,30] The components and their functions are very similar in the two models, but the size of XI-A permits the use of full-size

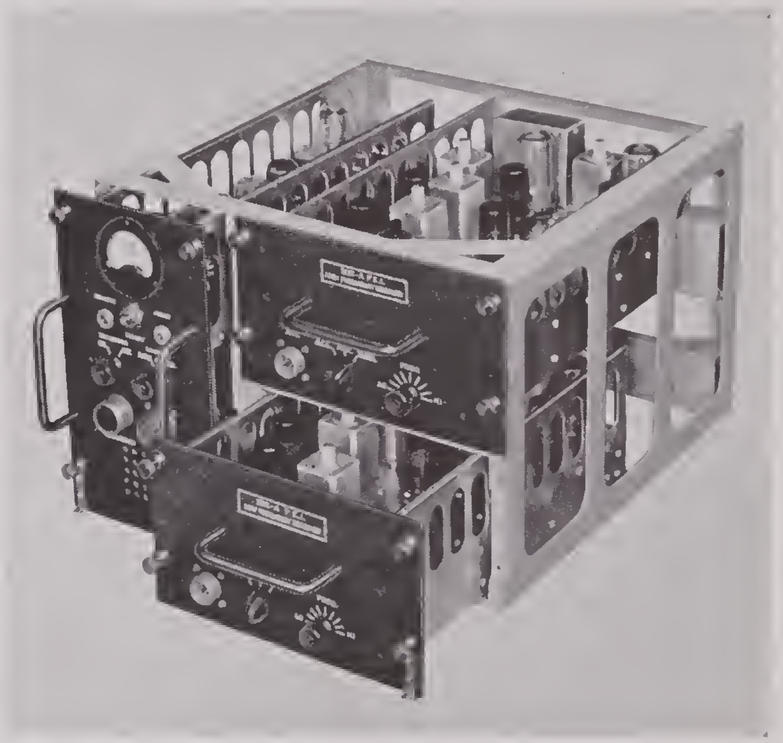

FIGURE 31. Photograph of aperiodic dual r-f FEI receiving station Model XI-A.

rather than miniature tubes and affords better accessibility for servicing. The upper and lower drawers on the right-hand side contain the two independent r-f receivers. These convert the f-m radio signals from the two units in the transmitter into audio-frequency signals delineating the separate responses of the microphones to the impinging N-shaped shock-wave excitation. These drawers also contain the audio band-pass filter network for each microphone channel. The single drawer on the left contains the audio-frequency circuits which pulse-lengthen the shock-wave signals, combine them to form the sum signal and the signals indicative of directionality and classify the sum signal into the three miss-distance zones.

The block diagram of Figure 32 illustrates the functioning of the receiver. Complete schematic wiring diagrams are given in Figure 33A and B. On the block diagram of Figure 32 the dotted lines separate the contents of the

three different drawers. The two r-f signals from the microphone units have frequencies of 56.75 and 55.5 mc, respectively. These are received at 1 and amplified in blocks 2 and 3. If it is desired to operate more than one FEI system in a given locality, other pairs of frequencies with similar spacing in this general region can be used by slight realignments in the local oscillators of the different receiving stations and corresponding changes in the transmitter-oscillator adjustments. The readjustment of transmitter frequency (radio frequency) also implies its restandardization for frequency shift in response to static pressure on the diaphragm, procedures normally performed by the manufacturer. It is recommended therefore that transmitters adjusted for a different carrier frequency be ordered separately from the factory.

The antenna cable is provided at 1 with a special shielded bifurcation point from which two short cables, connected in parallel at 1, lead through connectors on the panel to the antenna coils of the two receiver channels. The lengths of these two short cable leads are carefully proportioned so as to be equivalent to one-quarter wavelength. All three cables have a characteristic impedance of 100 ohms and the antenna coil which terminates each line is matched to this same impedance for its own signal frequency. For the signal frequency of the other channel, however, the antenna coil presents a terminal impedance, Z_o, of only about 15 ohms. Thus, at the junction point, 1, the input impedance, Z_i, of either channel to the frequency intended for the other channel is high, being given by the equation relating input and terminal impedances for a quarter-wave line, namely,

$$Z_i = R^2/Z_o. \tag{4}$$

As a result, at the junction point, 1, each cable accepts r-f signals of the appropriate frequency for its channel and rejects r-f signals of the frequency of the other channel. The use of this cable assembly without modifications in the lengths of the bifurcated leads is, therefore, essential to proper functioning. The length of the cable from antenna to junction point 1 is immaterial within limits. About 50 ft may be used.

After amplification in blocks 2 and 3 of Figure 32, the r-f signals are then mixed with local oscillator frequencies generated in blocks 4 and 5, so that at the points 8 and 9 there appear the separate and distinct f-m signals for each microphone channel at intermediate carrier frequencies (i-f) of 9 and 10 mc respectively. These are then amplified in two i-f stages (blocks 10 and 11). The amplitudes of the i-f signals fed to the discriminators for conversion from f-m into audio output must be maintained at a very constant level independent of the fluctuations of the r-f signal amplitude received at the antenna (because of varying transmission distance and other conditions affecting r-f signal strength). This constancy of i-f amplitude is maintained over a wide range of input-amplitude fluctuation, in part by the automatic volume control fed back from the limiters, 12 and 13, on the lines marked "AVC," but principally by the (conventional) operation of the two-stage limiters themselves. The AVC serves the further function of furnishing voltages, indicating the received signal strengths, which, in the normal position of a spring-selector switch (at the point marked AVC on the panel of Figure 31) appear on the panel meter and indicate the degree of saturation of the limiter. The operator, thus, has a means of observing, when the received carrier-signal strength is falling, whether it is approaching dangerously near to the lower limit for reliable operation.

The f-m, amplitude-limited signals are converted by the Foster-Seeley type discriminators, 14 and 15, into low-level audio-frequency signals at points 16 and 17. The signals at these points duplicate electrically the mechanical motions of the respective FEI transmitter microphone diaphragms in response to the N-shaped shock-wave excitation, as indicated by the sketched wave profile on the block diagram. It will be observed that the discriminator output voltage is also used to furnish automatic frequency control [AFC] to the local oscillators, so that slight and moderately slow drifts of FEI-transmitter frequency are automatically followed so as to maintain the i-f carrier frequency in the receiver at the correct constant value. (The circuit constants are such that the rapid changes in i-f frequency, of which the shock-wave signals from the microphones consist, cannot be followed by the AFC. Indeed,

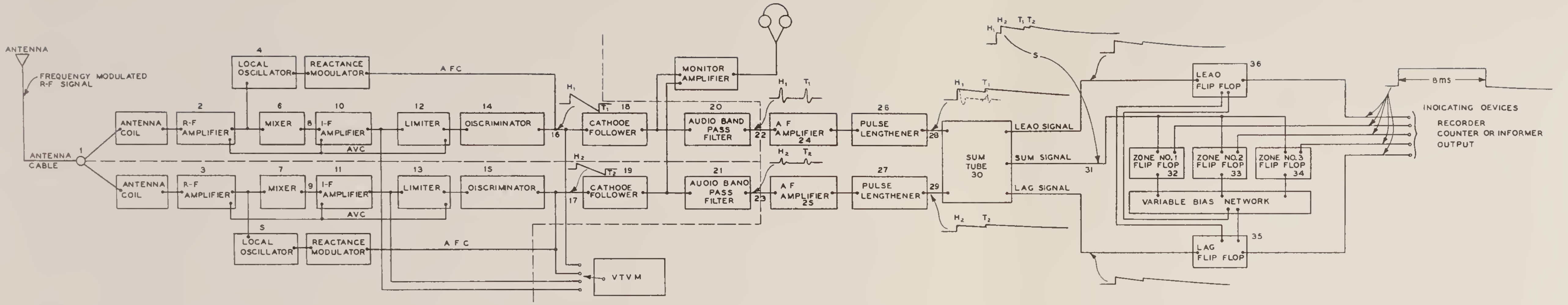

FIGURE 32. Block diagram of receiving station. Typical pulse wave shapes are shown in pulse section of receiving station. Dashes — — — separate independent sections of receiving station.

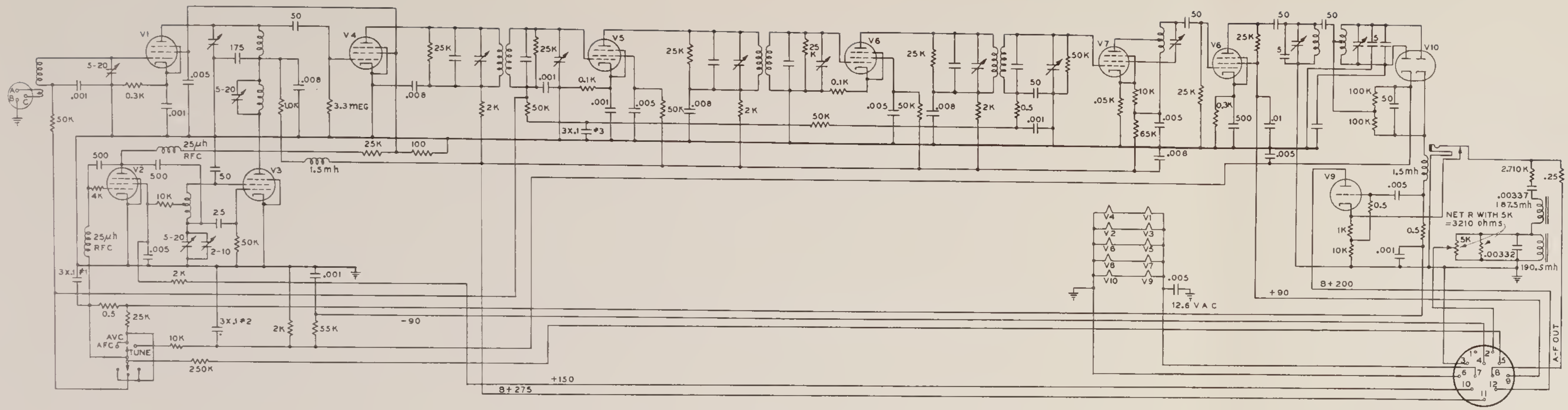

Figure 33A. Schematic wiring diagram for receiver section.

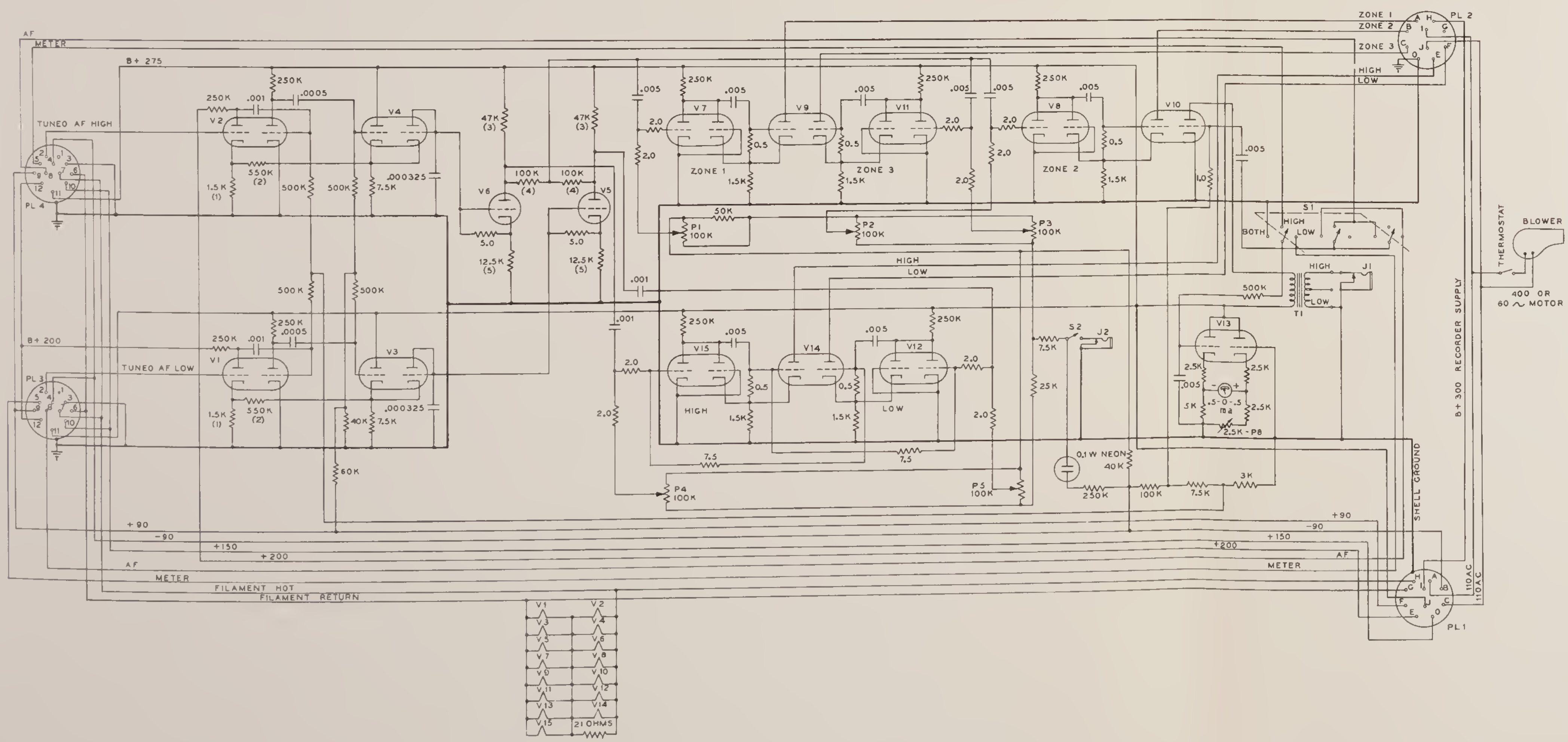

Figure 33B. Schematic wiring diagram for audio and zoning section.

the audio frequencies below 200 c, which this arrangement suppresses, are far below the range excluded by the audio filters 20 and 21.)

The receiver in use must be first manually tuned until it picks up the transmitted signal. The AFC can then be turned on to operate automatically. While this initial manual tuning is being done the spring selector switch on the front panel (Figure 31) is held in the position marked "tune" and in this position the AFC is automatically disconnected and the panel meter connected to show the discriminator voltage. As the tuning button (marked "Freq." on the panel) is exploring across the transmitter frequency, the discriminator voltage will pass through the familiar positive and negative peaks joined by the intermediate linear working range. Tuning is correct when the meter indicates the zero point at the center of this linear range. The spring switch can now be released and allowed to return to the normal working position (marked AVC because, as already explained, the panel meter then indicates the AVC voltage). In this position the AFC is automatically operating. A third position marked AFC is provided in which the AFC is still operative but the discriminator voltage is thrown on to the panel meter in case it is desired to check whether the AFC is operating correctly.

A ready light under the panel meter indicates, when lighted, that both channels are operating

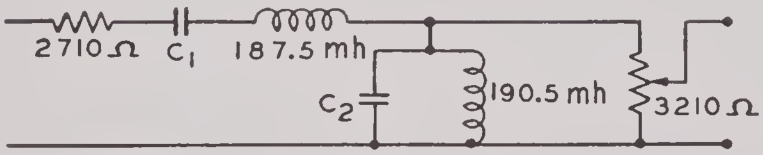

FIGURE 34. Diagram of audio band-pass filter, with circuit constants.

correctly with ample radio-signal strength to saturate both limiters. In this condition only, a relay is closed which permits the tape recorder, or the integrating shot counters, to operate. If the tuning is faulty, or the received radio signal strength too low, the light will flicker or be extinguished. Such disturbances can occasionally produce spurious shot records which must be deducted in scoring.

The two N-shaped audio-frequency microphone signals at 16 and 17, Figure 32, after suitable impedance transformation in the cathode-follower stages 18 and 19, pass through the highly important audio band-pass filter networks 20 and 21. These filters have carefully designed band-pass characteristics which are down 3 db from mid-band value at 4,000 and at 10,000 c respectively, and which have ultimate

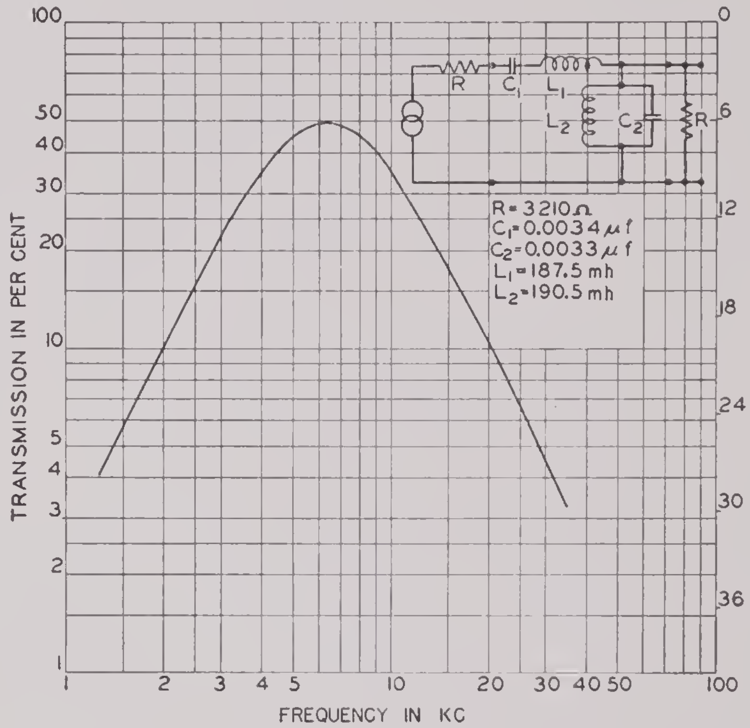

FIGURE 35. Frequency response of audio band-pass filter and equivalent filter circuit.

slopes on either side of about 12 db per octave. The schematic diagram of this filter together with specifications for its adjustment appear in Figure 34. Figure 35 gives the frequency-response curve. This filter eliminates low-frequency noise disturbances but retains the two discontinuities, *H* and *T*, of the shock wave in the form of two transient pulses as indicated in Figure 32 at the points 22 and 23. By detailed mathematical analysis[30b] of the transient response of this filter it has been shown that the higher of the two pips which it gives in response to the *H* and *T* discontinuities is, to sufficient accuracy, proportional to the N-wave peak amplitude and independent of the N-wave period within the limits of 0.3 to 1.5 milliseconds. Figure 36 shows the transient responses of this filter to N-waves of different periods as calculated in the aforementioned analysis.

The analysis shows that the average of the two pip amplitudes would have had even better characteristics in this respect, but too many circuit complications seemed to be involved in order to utilize this fact.

The properties of the filter are such that essentially only the step discontinuities of the N wave come through

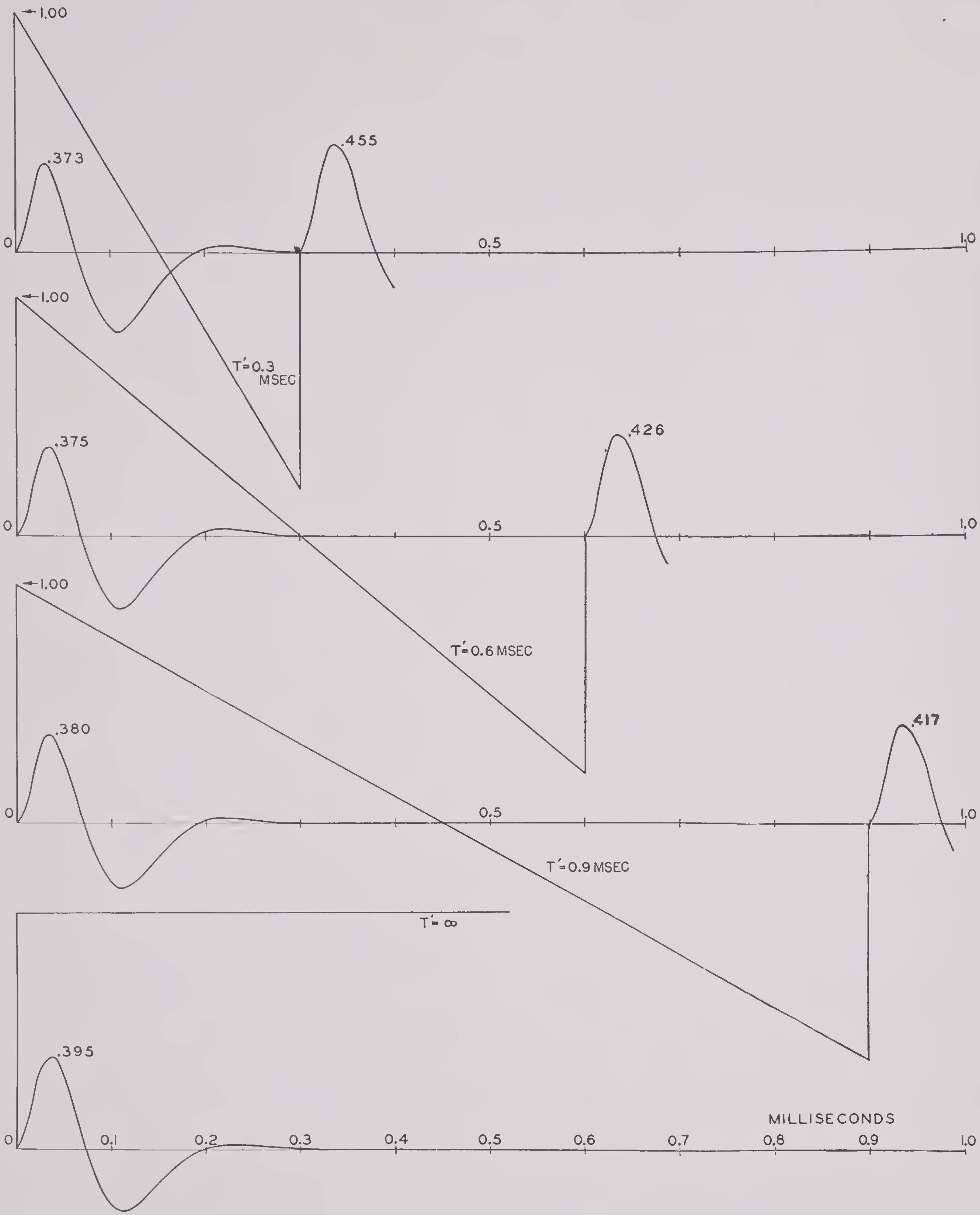

FIGURE 36. Transient responses of audio band-pass filter to N waves of different periods.

it; the relatively slowly varying intermediate linear decline in the N wave, as well as the accidental irregular disturbances from noise and other causes, are almost completely suppressed. The filter has the further property that the pip output which it furnishes in response to each input step discontinuity has a peak amplitude nearly proportional to the height of the input step and independent of the abruptness of rise of the step provided that abruptness exceed a certain minimum. This minimum has been chosen so that all N waves to be handled by the filter are considerably more abrupt than necessary. (The order of magnitude of the abruptness of shock-wave discontinuities has been estimated from the theory of their propagation. See Appendix III.[3] For very intense and hence abrupt N wave pressure steps the microphone diaphragm is the limiting factor in the abruptness of rise of the transient input to the filter, however.) The pip amplitude is slightly affected by the slope of the linear portion (period) of the N wave because of the finite time of rise of the pip. The *H*-discontinuity pip is slightly diminished and the *T*-discontinuity pip slightly increased by this effect. (This is the reason why the average of the two pips would have been a slight improvement.) The filter has furthermore been designed so that the *H*-transient pip damps out rapidly enough to avoid any appreciable *superposition* on the *T*-pip for N wave periods down to 0.3 millisecond. These qualitative statements can be verified quantitatively by reference to OSRD 4968,[30b] or to Figure 36.

These transient pips at 22 and 23 do not coincide in time in the two channels because the two microphones do not receive the shock wave simultaneously. This time displacement, which may be of order 1 millisecond, would prevent addition of the two microphone signals to form the sum response, unless pulse lengthening is used. After appropriate audio amplification at 24 and 25 (with a high-stability voltage gain of about 250 through inverse feedback) the pips are pulse-lengthened at 26 and 27 in such a way that the lengthened pulse exhibits a decay to half its initial peak value in 6 milliseconds. At points 28 and 29, therefore, the pulse-lengthened signals look as sketched on the block diagram. The pulse-lengthening consists merely in causing the voltage pip to charge a condenser through a rectifying element. A high-resistance shunt leak across the condenser determines the above-mentioned subsequent decay rate of the pulse-lengthened voltage. Clearly, such an arrangement is noncumulative so that the higher of the two pips will dominate in determining the pulse amplitude.

Since the top of the pulse is nearly constant for the first millisecond (the decay being only about 10 per cent in that time) it is possible to combine the signals from the two channels in spite of their incomplete simultaneity. This is done in the "sum tube," 30 of Figure 32. The sum of the two pulse-lengthened signals appears at 31 with shape as indicated in the sketched curve *S*. The highest point reached on this curve is the sum-signal amplitude which according to its level is selected or rejected by one or more of the zoning elements or "flip-flops." For purposes of scoring it is desirable to classify the shots in the three zones of predetermined radii and this function is performed by the zoning flip-flops.[m]

A flip-flop is an electronic network which can be tripped by a very short impulse to give a rectangular plate pulse of fixed duration and fixed amplitude. Whenever the input tripping pulse exceeds a certain amount, the flip-flop will trip independent of the amount by which the triggering pulse exceeds the tripping threshold, and it will then furnish for a standardized length of time a plate signal which can be used on the recorder or counter. These networks are designed to have very sharp thresholds. The peak value of input pulse at which flipping occurs is adjustable by means of bias potentiometers, and it is with these that the sizes of the miss-distance zones of the target can be set for a given caliber. The threshold for tripping is greatest for zone 1 and least for zone 3. For a very close miss (in zone 1) the sum signal is sufficient to trip all three flip-flops; for a zone 2, two flip-flops; for a zone 3, only the one flip-flop with the lowest threshold.

Two more flip-flops, 35 and 36 in Figure 32, are so interconnected that one or the other of them trips according to which signal comes first. The channel signals must, however, exceed a certain bias threshold in order to do this. This threshold cannot be set lower than reliable operation and freedom from accidental disturbances permits. It is this threshold setting which fixes the maximum lateral sizes of the two directionality lobes of the transmitter. Since it is not the sum response which is operative in tripping the directional flip-flops, but one of the two individual channel responses, the lateral extension

[m] This method of zoning with flip-flops has replaced the earlier method with mechanical relays used in Model XI and explained in OSRD 4967[29] and 4968.[30] For an explanation of flip-flop or trigger circuits see reference 45.

of the directionality lobes must be dependent on the orientation of the microphone axis relative to the bullet trajectories and on the apex angle of the shock-wave cone. The changes in the shapes and sizes of the directionality lobes with the various parameters on which they depend is explained in detail in Appendix II.[2] This system in which the directionality-lobe boundary is fixed by the level of the signal from a single microphone, the earlier of the two, and the later microphone signal is completely ignored, is a marked improvement over earlier systems in which the lobe boundary was fixed by the difference in level of the two microphone signals or by some linear function of the signal levels (weighted difference). As a result of this improvement, the dimensions of the directional-response lobes on the two sides of the transmitter do not become unbalanced so rapidly as the aspect angle departs from zero. The limits of correct directional response, however, remain unchanged. The choice of directionality indication is thus made on the basis of which microphone reports its signal first, not as in earlier models on the basis of which signal is the most intense. A little thought, however, will convince the reader that the result is the same. If reference is made to Figure 15, it can be seen, for example, that within the "reliable range" of correct directionality indication the microphone which will receive the shock wave first is the one on the same side of the transmitter as the trajectory of the bullet.

The output plug from Model XI-A thus contains a total of five channels, one or more of them being activated as the bullet passes through one or more of the five regions (three miss-distance zones and two directionality lobes). Either a tape recorder or a counter can be connected to the output terminals.

Beside the main Model XI-A chassis, a separate power-supply chassis is required.

2.6.6 Specifications of FEI Receivers XI-A[33]

DIMENSIONS

Receiver. Three-drawer Model XI-A, C2-C, Standard Aircraft radio chassis, dust cover 16x11x16 in., shock mount assembly MT 172-U, total weight 40 lb.

Power supply. B2-C Standard Aircraft radio chassis, dust cover 15½x11x10½ in., shock mount assembly MT 170-U, total weight 80 lb, antenna cable, Twinax cable 95-ohm characteristic impedance.

RECEIVING CHANNELS

Two channels; one r-f stage in rack; two i-f stages in rack; two limiter stages; Foster-Seeley type discriminator.

R-f tuning range: 55.5 mc ± 0.25 mc (lag channel), 56.75 mc ± 0.25 mc (lead channel). (It is also possible to supply 58.25 mc ± 0.25 mc and 59.5 ± 0.25 mc.)

Tuning: local oscillator only, AFC provided.

Intermediate frequencies: 10 mc (lag channel); 9 mc (lead channel).

Local oscillators: oscillator doubler *below* radio frequencies; 22.75 mc (lag channel); 23.875 mc (lead channel).

Mixer: Inductive mixing and grid leak first detector.

R-f input voltage to saturate limiter at center frequency: 40 μv (approx).

Impedance at antenna terminals: 95 ohms ±40 ohms.

Discriminator slope: 15 kc ± 3 kc per volt (approx).

I-f band width: flat response to ±10 per cent over 200-kc width.

Linear range of discriminator: linear to ±3 per cent over 150 kc.

Discriminator slope: 15 kc ± 3 kc per volt.

AFC gain (reduction factor in voltage at the discriminator when AFC is connected): 1:30.

AFC hold-in range: ±1 mc.

AUDIO CHANNELS

A-f band-pass filter: L-section constant *K* confluent band-pass filter as shown in Figure 34 with frequency-response characteristic shown in Figure 35.

A-f gain (with feedback) beyond filter: 290 (approx).

Inverse feedback of a-f amplifier: 10 db (approx).

Frequency flatness of amplifier: ±4 per cent from 1 kc to 10 kc.

Pulse-lengthener time constant: 9 ± 2 milliseconds.

Minimum permissible time between input bullet signals: 50 milliseconds.

Power Supply

Input supply: 115 v, 60 c or 400 c.

Output: *a*, 275 v direct current, 180 ma; *b*, 300 v direct current, 30 ma; *c*, —90 v direct current, 5 ma; *d*, 12.6 v alternating current, 8 amp.

2.6.7 Recording and Indicating Equipment for the FEI

Electrographic Tape Recorder

This component has been already adequately illustrated and described in Section 2.5.4.

Dial Counters

The dial-counter chassis assembly has been described and pictured in Section 2.5.4. Some detailed information regarding the dial counters themselves is given here.

For this application a small, light, compact dial impulse counter was needed capable of counting random impulses as closely spaced as 50 milliseconds (twenty counts per second to meet the needs of machine-gun fire) and preferably of high input impedance and very low power requirement so that it could be driven directly from the flip-flop output of the XI-A receiver. Specifically, the driving electric pulse consists of an (approximately) square wave of current of 5-ma peak value and duration about 8 milliseconds. Each counter chassis assembly requires five such dial counters, three for miss-distance zone indication, and two for directionality indications.

In earlier models Cenco dial impulse counters had been used but, owing to the low impedance and high power requirement of these counters, it was necessary to build a special separate power-supply chassis solely for driving the five counters which when designed to meet the Aircraft Radio Laboratory specifications was rather bulky and weighed over 60 lb. This was objectionable especially in the Air Force application of the FEI.

To meet this difficulty, a miniature counter was designed in May 1945, and manufacturing development was begun with the Doelcam Company (West Newton, Mass.) during June and July 1945. The general mechanical design and dimensions are similar to a small dial counter with the difference, however, that the counting-speed requirement in the present case is much lower and the current pulses must be of 5-ma peak value instead of 300 ma as in Neher's case. The mechanical parts of the counter are built by adapting parts from a Waltham stop-watch movement. Figure 37 shows the external appearance of the counter. A main dial is provided on which 100 counts are indicated by the larger pointer and a secondary dial indicates up to 30 revolutions of the main dial, so that a total of 3,000 counts

Figure 37. External appearance of miniature dial impulse counter.

can be recorded. A reset knob, visible in the figure, is provided to reset both dials back to zero. The frame casting has an outside diameter of 2⅞ in. and the dial is about 1¾ in. in diameter. Figure 38 is a view of the counter mechanism removed from the case. The electromagnet coils (15,000 turns of No. 44 wire, inductance 8.3 henrys at maximum air gap) have special alloy cores which by special heat treatment have a permeability, $\mu = 50{,}000$ (approximately) in the flux density range of 4,000 to 8,000 gausses.

Insufficient time was available to test and develop this counter because the work was terminated earlier than had at first been expected. The first examples of the counter were

received from the manufacturer in September 1945. Tests of their operation on the square-wave 5-ma driving impulses showed all but one or two to require more than the specified current and they were returned to the factory for readjustment of armature-spring stiffness. Late in October 1945 five of the readjusted counters had been received and tested. After some study, satisfactory performance on the

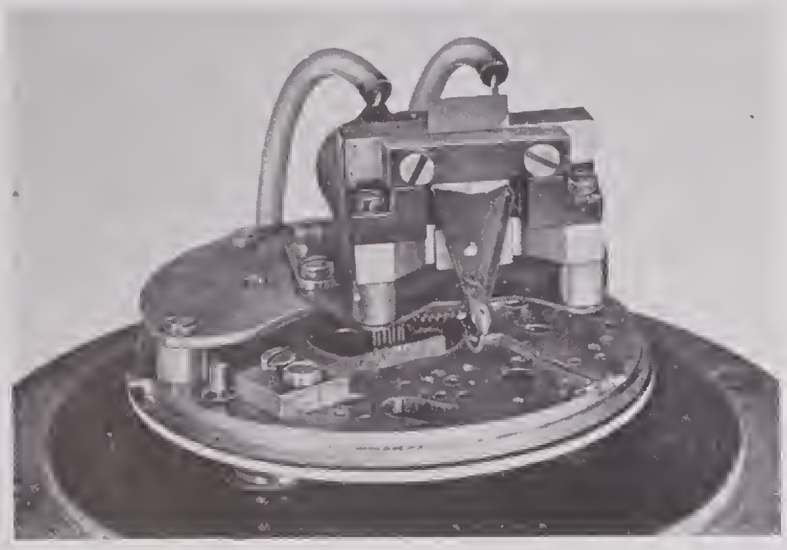

FIGURE 38. Internal view of miniature dial impulse counter.

output pulses from Model XI-A receiver at 20 pulses per second was obtained. It appears that one source of difficulty in the action of the counter comes from residual magnetism in the core material. It has been found that advantage can be taken of an inductive reverse surge of current at the instant the circuit is broken to neutralize this residual magnetization. The termination of this work leaves the counter development in a less thoroughly completed state than could be desired.

INFORMING BY LIGHTS

On the panel of the dial counter assembly a neon light is provided for each counter to give more easily observed indications when hits occur in the several zones of radial miss distance or lobes of directional response. Such lights are particularly useful in aircraft applications where an instructor operating the FEI receiver wishes to give the trainee gunner immediate information regarding his successes or errors after each burst of his fire or immediately after a pass of the target.

2.6.8 The Quantitative Standardization of FEI Response

NEED FOR STANDARDIZATION

The aperiodic FEI differs radically from most radio-acoustic devices by being a quantitative instrument all of whose elements must be standardized so that measurements made with them shall have a uniform and reliable interpretation for scoring purposes. Without this precaution comparative scores made in different places, at different times, and with different equipment would be meaningless.

It is here outlined very briefly how this is accomplished. Further details as to the instruments and procedures are given in Appendices IV[4] and V.[5]

The three main steps which insure that the shock wave from a bullet of a given caliber (for instance 40 mm) missing the target (by 4 yd, the smallest zone boundary) will on the average give a sum signal in the receiving station which will just trip the flip-flop for Zone 1. To have this happen, many different adjustments in both the FEI transmitter and receiver must be correct, but the entire process can be summarized by listing the three essential steps.

STEP ONE, TRANSMITTER STANDARDIZATION

The radio frequency of each f-m transmitter must shift by a standardized amount in response to a standard pressure (or force) applied to its microphone diaphragm. This is done by the transmitter manufacturer with a static pressure applicator of special design applied to the microphone diaphragm. A static pressure of 40 mm of Hg has been selected as the standard value which must produce in each FEI transmitter (for both microphone-oscillator assemblies) a shift of 100 kc.

This may also be accomplished by applying a standard weight of 50 grams with a bearing surface of standard curvature (¼-in. diameter ball bearing) to the center of the microphone diaphragm by means of a special jig. The pressure method has been found somewhat preferable and more reproducible, but either method can be used. For the FEI microphones, 4 cm of mercury pressure produces the same (100-kc) shift in transmitter frequency as the 50-gram

weight seated on a contact of ⅛-in. radius of curvature at the center of the diaphragm.

When the weight method of standardization is used a small jig, which centers the point of application of the 50-gram weight, is placed over the machined shoulder on the periphery of the microphone. The weight is placed on a small platform on the end of a stem fitting very smoothly in a lapped bearing in the jig, the lower end of the stem having the ball bearing as its termination.

When the pressure method of standardization is used, a small cup provided with a very thin rubber membrane over its open end is applied so that the membrane lies flat on the microphone diaphragm. Air pressure is pumped into the cup through a nipple connection and this pressure is read with a manometer.

The standardization procedure then consists in adjusting the transmitter trimmer condensers, C_1 and C_3 (Figure 30) to give correct undisturbed carrier frequency (without pressure applied to the diaphragm), and correct frequency shift (100 kc) in response to the standard pressure on the diaphragm. Since the two adjustments are not independent some skill and experience is required. The procedure is a factory operation. (Condenser C_2 must also be adjusted to peak the r-f output.)

A transmitter standardizing instrument (described in Appendix V[5]) has been developed, furnishing a means of checking both the undisturbed carrier frequencies in the transmitter and the frequency shifts under diaphragm pressure. This instrument uses crystals to standardize the frequencies.

STEP TWO, STATIC FIRING

After an FEI transmitter is standardized as in step *one*, measuring the miss distances from experimental static firing of the calibers desired with theodolites, a frequency shift vs miss-distance curve is obtained for that caliber. From this the frequency shift Z_1 for 4 yd, the radius of Zone 1 for example can be read. (The frequency shift referred to is the sum response of the two microphones.) Other zones are calibrated similarly.

STEP THREE, RECEIVER STANDARDIZATION

The discriminator slope, the audio-frequency amplifier gain, and the zoning threshold bias of the receiver are to be adjusted so that when a sudden measured shift of Z_1 kc is received by special means at the antenna with an abruptness simulating the shifts produced by the shock-wave discontinuities, the Zone 1 flip-flop will just respond. Checking equipment for injecting such frequency modulations has been developed both for use of the Services and for the initial standardization of receivers at the factory. This is called an E-checker. Its description is given in Appendix V.[5]

It will be noted that steps one and two combined, constitute a determination of peak shock-wave pressure and this is a result which should be expected to remain constant for a given caliber, velocity, and miss distance without need for repetition. (To obtain the pressure elevation in the free shock wave from the above method it is also necessary to know the reflection coefficient at the diaphragm and possible minor corrections to allow for the obscuring effect of the protecting screen over the microphones.) Neither of these two steps considered alone, however, has this character. It is therefore very important to emphasize that if any changes from the present physical design of microphone and transmitter are made, these may make it necessary to repeat step *two* by as extended a program of static firing as has already been undertaken in this work. Apparently minor and innocuous changes which may even be improvements as far as the functioning of the equipment is concerned must be considered carefully from the point of view of their effects in necessitating a long and expensive recalibration with static firing (with all pertinent calibers, at all requisite miss distances, aspect angles, etc.). So small a matter as the character of the protecting screen over the microphone is an example of just such a nature. A change from a screen obscuring 5 per cent of the exposed area to one obscuring 10 per cent would throw in question the entire present calibration status. The same thing is true as regards external geometry of the plastic hemispheres and the transmitter mounting.

It is probably wise to consider that a certain amount of occasional checking of the FEI transmitters with static fire may always be called for, even if no changes in design are made. Such checking need not be more fre-

quent than seems indicated by field results, and the naturally recurrent desire on the part of the Armed Forces to be assured of uniformity as to score.

2.7 BRIEF HISTORICAL REVIEW OF PROJECT

2.7.1 Early Attempts to Solve Problem

As already stated, the research and development of the FEI did not originate in a Service request. The need for such a device was first called to the attention of CIT personnel through witnessing target practice on airborne targets.

At the outset the objective of informing the gunner as to his errors of fire (if possible while the errors were being committed or immediately afterward) was the uppermost consideration. The use of the FEI to score marksmanship on a quantitative rating scale was an application emphasized later by the Armed Forces. Secondary interest attached also to the question of the direction of the error of fire, chiefly for the informing function. This is referred to as the indication of directionality. Thus at the outset the problem was regarded and approached as a qualitative one and emphasis on its quantitative aspects for scoring purposes emerged gradually as liaison with the Armed Forces became closer.

The first effort to solve the problem was made with magnetized bullets. It was found that a .30- or .50-cal. bullet, magnetized before shooting, would retain 70 to 80 per cent of its magnetic moment when examined after impact in sand. The traveling dipole magnetic field was picked up by circular hoop-shaped coils of various diameters (1 to 3 ft), at some distance from the trajectory, the brief induced electric pulse being amplified so as to indicate the miss distance by its intensity. At miss distances of 2 or 3 yd, however, the voltage amplitude of the pulse became very low. The law of decay of this voltage for a single pickup coil is the inverse fourth power of the distance, because the static dipole field intensity diminishes as the inverse cube and the time rate of change of this field diminishes as the inverse first power of the distance. The induced voltages in such a single pickup coil, coming from unavoidable aerodynamic vibration in the earth's field incident to towed flight, turned out to be of the order of 100,000 times larger than the pulses to be detected from .50 cal. bullets missing the coil by a couple of yards. To overcome this, two identical coils with windings connected in opposition and spaced about one diameter apart were rigidly coupled mechanically so that the interference from the earth's field would largely cancel out while the nonuniformity of the dipole field of the bullet would continue to give a signal. Such a differential signal diminishes as the inverse fifth power of the miss distance.

2.7.2 Abandonment of Magnetic Method in Favor of Acoustic Method

In the course of these experiments the acoustic shock waves from the passing bullets proved to be one of many annoying sources of interference, and it was in this way that the idea of utilizing the acoustic shock wave for the desired objective was first conceived. The experiments with magnetized bullets showed the magnetic method to be extremely unpromising and fraught with many difficulties, because of the very low level of intensity of the signals picked up and the many sources of interference which are of far greater intensity. It was, therefore, abandoned in 1942 at an early stage of the work.

2.7.3 Aperiodic and Resonant Microphones

The idea of the resonant diaphragms for establishing two channels of information between airborne transmitter and receiver was proposed at a very early stage of the acoustic experimentation, late in 1942. Field tests and laboratory experimentation were at first conducted simultaneously on *both* resonant and aperiodic systems. In the summer of 1943, the resonant system appeared from this preliminary work to be sufficiently promising to warrant concentrating every effort exclusively on its development. This, however, was before the quantitative scoring application of the device had received so much emphasis from the Services. The serious faults in the acoustic-response pattern of the resonant system for

scoring did not manifest themselves, however, until a great deal of detailed study of the response patterns of the dual-microphone resonant transmitters had been made by static firing.

2.7.4 Empirical Field Work

These response patterns were studied by suspending the FEI transmitter from wires attached to a telegraph pole and firing rounds of different calibers placed as precisely as possible in a large variety of positions relative to the transmitter. It was necessary not only to explore the response for many such positions in the target plane and for many transmitter units, but also to do so for different orientations of each unit relative to the line of fire for different calibers and different ranges from gun-to-target. The empirical approach and the difficulty of interpretation of the response peculiarities coupled with the practical difficulties of arranging field tests at distant points with the use of Army ordnance, aircraft and other facilities made progress slow. Nevertheless, detailed field study was absolutely essential and indeed it was the results so obtained which emphasized the necessity for fundamental research on shock waves and their wave forms, without which eventual progress would have been impossible.

This detailed study was necessarily very time-consuming for the following reasons: (1) It had to be conducted by shooting bullets of the various calibers from Army ordnance at distant testing ranges with the collaboration of the Armed Forces when weather, Army programs, and facilities permitted. (2) Equipment for measuring the response at the receiving station had to be progressively developed as the requirements became better understood. (3) A very great many rounds had to be shot partly because: (a) placement of shots was not always satisfactory, (b) several rounds must be averaged in every case to reduce statistical fluctuations, (c) the approach was empirical with a great many unknown factors and possibilities to be tried and explored.

In addition to the static firing tests it was necessary to conduct many tests of the transmitters in actual towed flight in sleeves and flags because it was soon found that mechanical vibration, wind, and flapping noise and other interferences were problems calling for extensive study. In addition, the reliable performance of new transmitter unit designs under the severe treatment they received in towed flight tests had to be carefully checked by trial. Large numbers of transmitters had to be constructed for such tests since from four to eight were frequently lost in a single mission. Such tests had to be conducted with Army tow planes when weather permitted and the planes and personnel could be spared from regular duty. A certain number of such tests were conducted with actual firing of guns at the towed transmitter when this could be arranged.

Studies of the types described continuing through the year 1943 made it increasingly clear that the earlier optimism regarding the resonant system had been unjustified. It was found to have two major faults. (1) The resonant diaphragms were found to be very sensitive to the mechanical vibrations arising in towed flight, and to the characteristic noises connected therewith. (2) The sum-response patterns turned out to be not only very irregular in shape but, as already pointed out, the miss distance was not a single-valued function of sum response. For a given resonant transmitter, critical null response regions in the target plane existed, while at greater and at lesser radial miss distances, the sum response was well-defined. A given level of sum response might thus mean any one of several widely different miss distances. The difference lobes suffered from similar peculiarities.

These facts alone are sufficient to arouse the suspicion that the wave form of the shock wave has some sort of definite period which resonates constructively and destructively with the natural periods of the resonant microphones, and this was found to be the case after sufficient fundamental study on the nature, wave forms, and laws of propagation of ballistic shock waves had revealed the facts.

For a complete analysis and discussion of all the sources of error for the cases of both the resonant and aperiodic systems the reader is referred to OSRD Report 4966.[22]

2.7.5 Fundamental Research on the Physics of Ballistic Shock Waves

The difficulties encountered with the resonant system of firing error indication led, in October 1943, to initiation of an extensive program of fundamental research on the physics of ballistic shock waves, upon which the present design of aperiodic FEI is based. Space in this report permits mentioning only a few of the most important results. For more complete information, the reader is referred to Appendix III.[3]

Special oscillographic equipment was developed for recording wave forms of shock waves as observed with different microphones. A quartz piezoelectric microphone of extremely high period was obtained from the Bell Telephone Laboratories. The responses to shock-wave excitation of the resonant condenser microphones and also of aperiodic condenser microphones were also studied. It was found that the shock-wave pressure disturbance has an N-shaped profile, already alluded to. The very steep pressure steps in the wave and the variation in period (measured between the occurrence of these head and tail discontinuities) were striking features of this research. It was decided to utilize profitably the steep pressure steps in such a way as to differentiate the shock-wave signals from ordinary sounds. Very excellent direct photographs of shock waves made at Aberdeen Proving Ground, were sent from there to this project and a study of these was of the greatest help in interpreting the acoustic wave forms. Much insight into the mechanism of propagation of the discontinuities was gained from an article by R. Becker,[44] and it was in this way that a quantitative idea of their extreme steepness was formed, which gave reason to expect the presence of very high audio-frequency components in the shock-wave spectrum even at large distances from the bullet trajectory. The idea of using this fact to avoid noise interference by limiting the audio-frequency spectrum employed with a band-pass filter which would (1) eliminate noise, and (2) transmit the height of the N-wave discontinuity step as a transient pulse independent (within limits) of the N-wave period was at first only a "pious hope." It was not certain (1) that the signal-to-noise ratio could in this way be improved by filtration, and (2) that a filter having the required response to the transient excitation could be designed. A third uncertainty concerned the possibility of designing a microphone with flat frequency-response characteristics up to a sufficiently high frequency to take advantage of this plan of attack. The use of a flat-response microphone seemed attractive nevertheless since these components must have reproducible characteristics in a very large number of examples and a more complicated response curve would be more difficult both to specify and to reproduce. Also, it was soon realized that a flat-response microphone permitted a simple static standardization procedure (by the pressure, or weight, method) since the response over the working range becomes identical to the response at zero frequency.

2.7.6 The Aperiodic System of Firing Error Indication

Work on the aperiodic system, both along theoretical lines and in the field and laboratory, was started intensively early in the spring of 1944. It was not until late July of that year that the improvement in signal-to-noise ratio of the band-pass filter was verified (4,000 to 10,000 c).[26] This was a very important result for the success of the device. Much time and effort had been spent in mathematical analysis on this filter design and on the calculation of its response to the N-wave transient.[30b]

Problems concerned with the technique of reproducible microphone manufacture and stability occupied a large place in this work throughout its entire duration and efforts tending toward improvements along this line continued almost up to termination of the work. A complete history of all the phases of this problem, in the evolution to the present manufacturing procedure, would be too long for this report. The reader is referred to Interim Progress Reports[8,9,10,12,14,17,19,20,21,23,26,27,28,31,34] for such information.

Actual validation of the scoring accuracy of the aperiodic FEI in towed flight did not come until very late (May and June 1945). This work, which required special camera equip-

ment and close cooperation with the Armed Forces was done at Ft. Bliss, Texas.[32]

The work for the Manhattan District in the application of the FEI to measurement of blast pressures from the atomic bomb was started in April 1945, and cooperation to that end continued until the termination of World War II.

Research and development on the FEI under NDRC terminated on October 31, 1945.

Chapter 3

MAGNETIC RECORDING RESEARCH

By *George E. Beggs, Jr.*[a]

3.1 SUMMARY

THIS REPORT DESCRIBES results of work on the two important phases of magnetic recording research, the development of recording methods and apparatus, and of magnetic signal carriers[b] of various types. The work was done under a contract with the Brush Development Company. Portions of the work on magnetic recording media were done under subcontracts with Battelle Memorial Institute and Case School of Applied Science.

A *magnetic transient recorder* [MTR] is decribed, having a frequency range extending from about 800 to 30,000 c, over which phase distortions are held to a minimum by special application techniques, also described.

The development of recording techniques introduced new problems in the field of recording materials. At the initiation of the program, available materials were not fully satisfactory for applications at hand, both from the frequency-response and the signal-to-noise ratio characteristics. Materials and methods for producing them were studied. Two were developed which have considerable merit, electroplated ribbon [ER], and a powder-coated tape [PCT].

The first type was produced by electroplating a thin layer of a magnetizable alloy onto a metallic, nonmagnetic base. The majority of the numerous platings developed consisted of cobalt-nickel alloys of controlled magnetic properties on a fine ribbon base of phosphor bronze.

The second consisted of a tape of either paper or plastic material, coated with a thin layer of a rather concentrated dispersion of a fine magnetic powder in a lacquer-type binder. From a number of powders investigated, synthetic magnetite (Fe_3O_4) was finally chosen because of its favorable magnetic and mechanical properties.

Both types of signal carriers exhibit frequency responses superior to hitherto commercially available recording media.

In connection with the application of this material, or modified forms of it, to magnetic recording, a new *ring head* [RH] was developed for recording and reproducing. It has reduced iron losses and an improved frequency response, is inherently hum-free, and can be produced in quantities because of its mechanical simplicity.

As a final result of the work under this program, the ground work for a theory of the mechanism of the magnetic recording and reproducing process was laid. The ultimate goal of this theory is the quantitative correlation between the performance of a magnetic signal carrier on the one hand, and its magnetic and mechanical properties on the other. Sufficient time was not available to complete work along these lines, but sufficient information was gained to allow the qualitative prediction of the performance of a given signal carrier.

3.2 INTRODUCTION

Ever since the recording of intelligence attained practical importance, the demand has existed for decreasing the amount of signal carrier required to store a given amount of information. This striving for economy has been apparent in all three dominant systems of signal recording; in the mechanical, the photographic, and the magnetic. Particularly in the latter field the trend is still in rapid evolution.

The principle of recording sound patterns upon a record of steel wire, tape, or similar materials has been known for many years. Valdemar Poulsen, a Danish engineer, introduced the method over forty years ago, and demonstrated his Telegraphone at the Paris Exposition in 1900.

The magnetic system of recording offers cer-

[a] Technical Aide, Section 17.1-17.2, NDRC.

[b] SC-111

tain advantages over other methods in several respects, but particularly in applications where records of a temporary nature are desired, inasmuch as the same recording material may be used over and over again to make new recordings after the old ones have served their purpose. In such instances, the carrier may be cleared (erased) and made ready for reuse by simply passing it through a magnetic field of appropriate characteristics, either alternating current or direct current, just prior to recording a new intelligence signal. Continuous recordings of long duration may be made upon a single carrier, thereby avoiding the necessity for multiple recorders or interruptions to change records. Furthermore, a magnetic recording may be reproduced hundreds of times without appreciable loss in signal level or quality.

The original problem considered under this program was the development of a high-frequency MTR to make a transient record for later continuous repetitious reproduction to permit observation on a cathode-ray oscilloscope. Magnetic recording was selected to alleviate the problem of multiple reproductions, ease of operation, small size, and reasonable power requirements. Early in this portion of the program, it became apparent that improvements in recording materials were needed to allow adequate frequency response of the system at usable signal-to-noise ratios. Thus the second portion of the program was concerned with the development of an improved magnetic signal carrier which would have these two qualities and an increased economy in the total required carrier volume for a given amount of intelligence.

In order to reduce this carrier volume, both its cross section and its velocity in recording may be reduced. The cross section of a carrier is mainly dictated by mechanical factors such as strength, and wearing and handling properties. Though a thin carrier is also desirable for performance reasons, there is apparently little room for the theoretical prediction of a minimum carrier cross section. Most of the work was concerned with the theoretical and practical aspects of improving the magnetic properties of the signal carrier.

3.3 THEORY

3.3.1 Elementary Considerations

Certain comments on response characteristics to be expected from magnetic recording processes will prove helpful in interpreting developments described later.

In the simplest approach, the recording flux will impress upon each point of the passing tape of magnetic induction which corresponds to the different instantaneous signal levels. This impressed flux may be called the internal flux [IF]. With longitudinal magnetization, used in the majority of magnetic recording studies, the external flux, as picked up by the recording head, must be proportional to $d\phi/dl$, where ϕ is the internal flux, and l is the distance along the tape. In other words, the external flux must be inversely proportional to the wavelength recorded, and therefore should increase 6 db per octave for constant recording. In playback, the voltage generated in the reproducing-head coils depends on the rate of change of flux. Therefore, one might expect a 12 db per octave increase in output voltage, and a phase shift of 180 degrees. This behavior can actually be observed, but only for very low frequencies, i.e., wavelengths about 1 in. or longer. For somewhat shorter wavelengths the rise has been found to be about 6 db per octave. The reason for this apparent discrepancy lies in an oversimplification of the preceding considerations. It appears that the flux through the reproducing head is determined not only by the magnetic state of the carrier element in actual contact with the head, but also by the adjacent elements on either side of it. The overall effect is one of adding or integrating the effects of the adjacent carrier elements. This integration of the second derivative (playback voltage dependent upon rate of change of flux) results in a playback voltage proportional to the first derivative of the signal, under constant current recording conditions, or a rise of 6 db per octave. For very low frequencies (long wavelengths), the effect of the integration is small, because of the rapidly decreasing influence of the adjacent elements with distance, which accounts for the observed rise of 12 db

per octave as explained by the oversimplified discussion.

With rising recording frequency, the output voltage should keep on rising with a 6 db per octave slope, if it were not for two additional effects which become more and more dominant. These are the effects of demagnetization of the elementary "bar magnets," and that of limited penetration. In this connection see Figures 1 and 2.

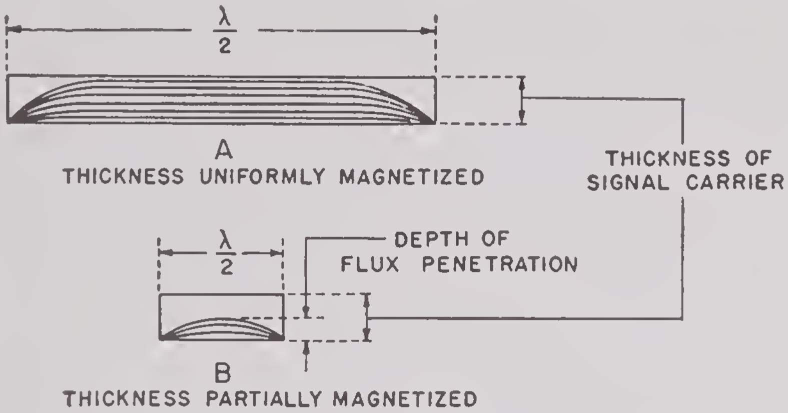

FIGURE 1. Penetration of recording flux into signal carrier at (A) long wavelength, (B) short wavelength.

3.3.2

Demagnetization

The demagnetization of magnets, that is, the weakening of their external field strength caused by their own magnetization, has been extensively treated in the literature, in particular for straight cylindrical rods. However, the immediate quantitative application of available data to magnetic recording problems is difficult for two reasons. (1) The elementary magnets in a magnetic sound carrier are linked together with their ends of like polarity adjacent, whereas the published data refer to magnets with free ends. The demagnetizing factors are consequently different in the two cases. (2) Because of limited penetration, the magnetization of the elementary magnets, for higher frequencies, is not uniform throughout the carrier cross section except for extremely thin carriers. This fact reduces the effective cross section of the elementary magnets and will therefore decrease their demagnetizing factors compared to those for full cross section. The situation becomes further complicated by some shunting effect of the remaining nonmagnetized portion of the carrier.

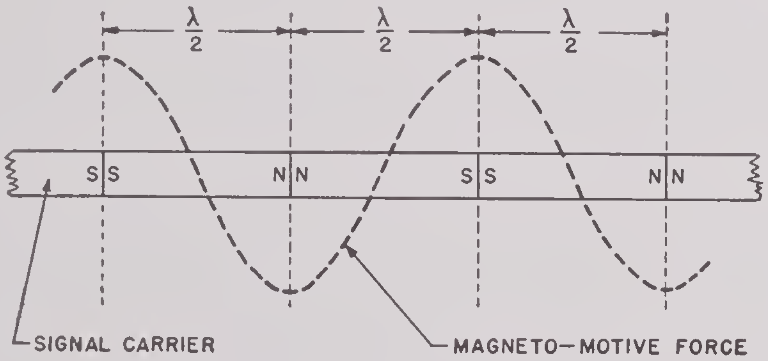

FIGURE 2. Arrangement of elementary bar magnets in signal carrier with sinusoidal signal recorded.

3.3.3

Coercive Force and Remanence

The determination of the flux available from a magnet is well known from the design of permanent magnets. Some discussion of facts derived from this design data will serve to clarify the discussion above, and will illustrate the possibility of assigning figures of merit to recording media.

In the second quadrant of the hysteresis loop (see Figure 3) containing the so-called

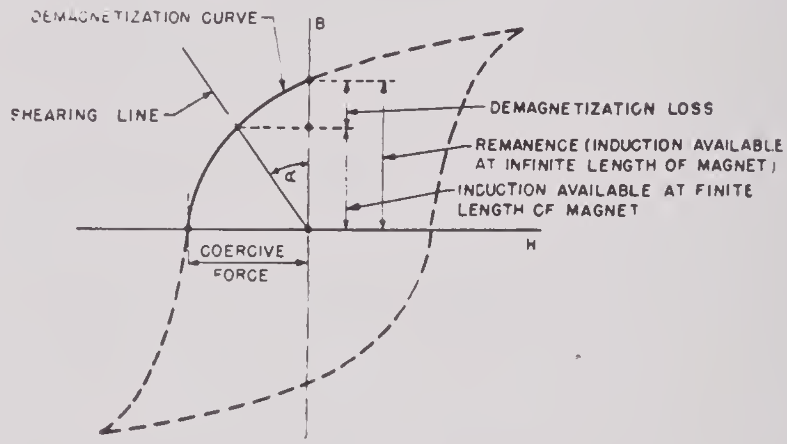

FIGURE 3. Effect of demagnetization.

demagnetization curve, a straight line (shearing line) is drawn from the origin at an angle α with the B axis. Tangent α equals the demagnetizing factor of the magnet. The point of intersection of the shearing line and the demagnetization curve defines the working point of the magnet, the ordinate of this point describing the available magnetic induction, or flux.

For bar magnets with a very high ratio of length to diameter, i.e., for long wavelengths and very small demagnetization, the shearing line is practically vertical and the available induction, consequently, identical with the remanent induction of the material. As long as the available induction remains close to this point, the response curve will follow very nearly the rising trend of 6 db per octave. With de-

creasing wavelength (increasing frequency) the demagnetizing factor increases and the working point slides down the demagnetization curve as the slope of the shearing line decreases. Accordingly, less and less induction becomes available for the generation of the playback voltage and the rising slope of the response curve decreases steadily.

The rate at which the available reproducing flux decreases depends—for a carrier of given dimensions and velocity—on the shape of the demagnetization curve. The greater its slope in any one point, the greater will be the loss increase in the corresponding point of the frequency-response curve. The correlation between these two quantities allows actual derivation of the response curve. In general, this derivation can only be made by graphic means, since accurate analytical expressions for either the demagnetization curve or the demagnetizing factors do not exist. The effects on the response curve can be visualized by reference to Figure 4.

A rather rough but quite useful rule can be derived from these considerations. Since the ratio of coercive force to remanence, H_c/B_r gives the reciprocal of the average slope of the demagnetization curve, this ratio can be used as a figure of merit expressing the suitability of the material for magnetic recording purposes. The greater the ratio, the smaller will be the rate at which the response curve falls off in the upper frequency range, for given physical dimensions and carrier velocity. While this figure of merit does not give fine details on response characteristics, it does give an idea of general performance to be expected. The rule has been tested and verified in many cases.

3.3.4 Penetration Effect

The penetration effect, mentioned above, further limits the high-frequency response, at least when RH's are used. Whether this effect, or the effective gap width, or demagnetization has the greatest limiting effect on the higher frequencies would be of interest in comparing plated vs homogeneous materials. Time did not allow these comparisons. The penetration of the high-frequency flux into the recording medium is limited because of the magnetic skin effect, and because of the geometry of flux distribution within the medium. The first effect is well known and needs no further explanation. The second one becomes clear from the fact that the flux from the RH enters into

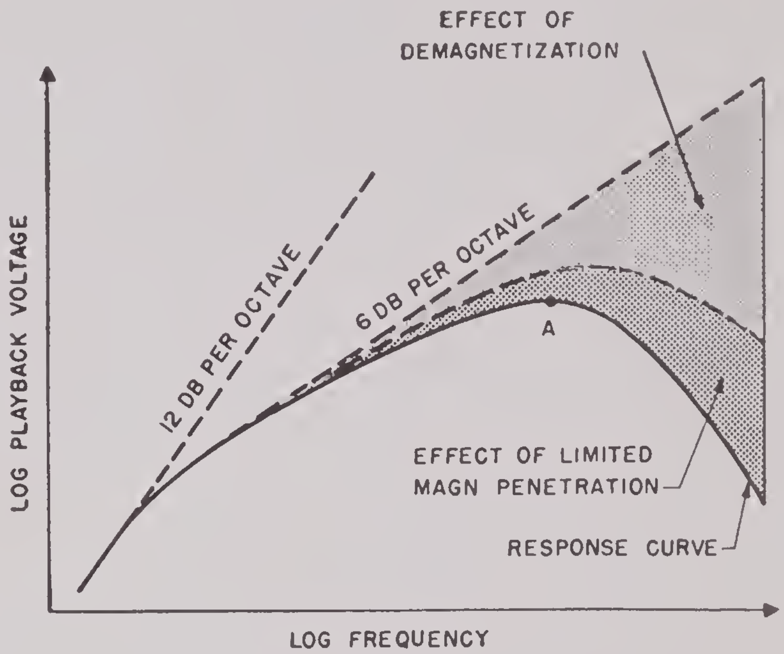

FIGURE 4. Evolution of frequency-response curve.

the recording medium at a small angle (depending, primarily on the magnetic properties of this medium) which makes full penetration of an appreciable thickness impossible at short wavelengths. (See Figure 1.) The wavelength effect appears to predominate under most conditions. Thus a further decrease in high-frequency response is noted, as illustrated in Figure 4.

An experimental proof of this penetration effect is the fact that the erasing with high frequency of a record on wire or tape, other conditions being equal, becomes increasingly more difficult as the recorded frequency *decreases*; i.e., the lower frequencies penetrate deeper into the recording medium than the higher ones, which may fall into the region that can be reasonably well penetrated by the erasing frequency.

A further evidence of limited high-frequency penetration is the effect from twisting of a round wire. For a given wire the level of the playback voltage decreases as the recorded frequency and twist angle between recording and reproducing heads increase. (See Figure 5.)

The above discussion outlines qualitative bases for the general form of response curve to be expected, as shown in Figure 4.

3.1 MAGNETIC TRANSIENT RECORDER

3.1.1 Military Requirements

The contractor was originally requested to develop an MTR capable of recording and reproducing transients containing frequencies in the range from 300 to 30,000 c, with good signal-to-noise ratio, low phase distortion, and provision for continuous reproduction of the recorded signal to allow its observation on a cathode-ray oscillograph. Total recording time of the order of 25 to 50 milliseconds was desired.

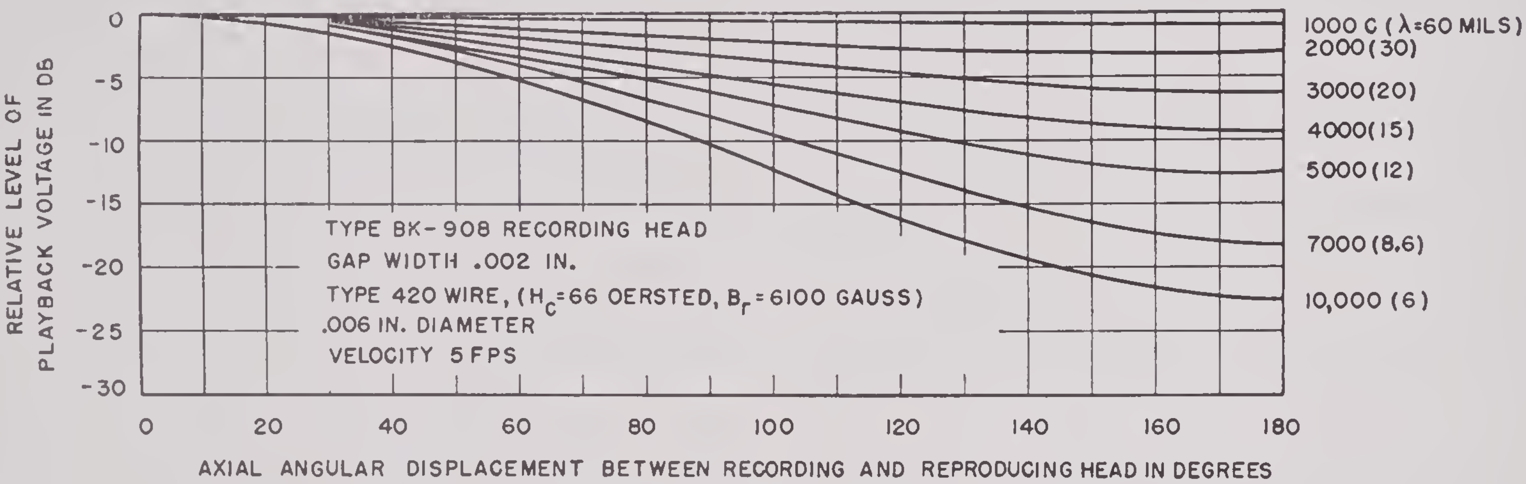

FIGURE 5. Effect of wire twisting upon playback voltage (experimental evidence of limited magnetic penetration).

3.1.2 General Methods Studied

Prior to the beginning of work on the development of the MTR, some work had been done in this field on a unit capable of recording transients with frequency components from direct current to 500 c.[13] In this instrument the transient is recorded on a loop of magnetic tape and played back synchronously every 0.2 second for observation on an oscilloscope screen. In connection with this work, the problem of phase distortion in magnetic recording was brought to the fore. However, in this particular case, since very low frequencies were to be recorded, while the high-frequency response was restricted, a carrier-frequency system was used, minimizing the phase-distortion problem. The carrier frequency was amplitude modulated by the intelligence frequencies.

With the advent of requirements for a recorder capable of handling frequencies up to 30,000 c, more than ten times the carrier frequency of 2,200 c used in the above-mentioned development, it was apparent that new techniques would need to be studied, to allow the higher frequencies to be successfully recorded, and to bring phase distortion to a minimum.

Initial tests on a high-frequency recording system were made, utilizing a tape about 3x120 mils, at a velocity of 35 ft per second. This velocity was an arbitrary choice, higher than expected for final apparatus, to allow partial elimination of this variable in studies on the effect of pole-piece materials, signal-to-noise ratio, and frequency response. The initial tape used was a tungsten steel alloy.

The actual recording method consisted of main flux longitudinal recording, using two flat poles, slightly offset, on opposite sides of the tape, as shown in Figure 6. In these tests obliteration and biasing were used. Results showed that signal-to-noise ratios were not satisfactory for the desired frequency-response range of 300 to 30,000 c, although actual response characteristics were encouraging.

Interesting data were obtained on the number of reproductions possible from a magnetic recording. Figure 7 shows the decay of signal as a function of the number of reproductions. Although these data were based on early experimental evidence, they serve to confirm statements made earlier concerning the number of reproductions available from magnetic recording media, one of the reasons this particular system was chosen for a transient analyzer.

3.1.3 Recording Methods

It is desirable to give a brief description of the two methods of recording that have been widely used in the field to explain the terms

d-c obliteration, d-c biasing, a-c biasing, etc. Prior to recording it is necessary for the tape to be placed in a uniform magnetic state. This may be a partially saturated state, obtained as

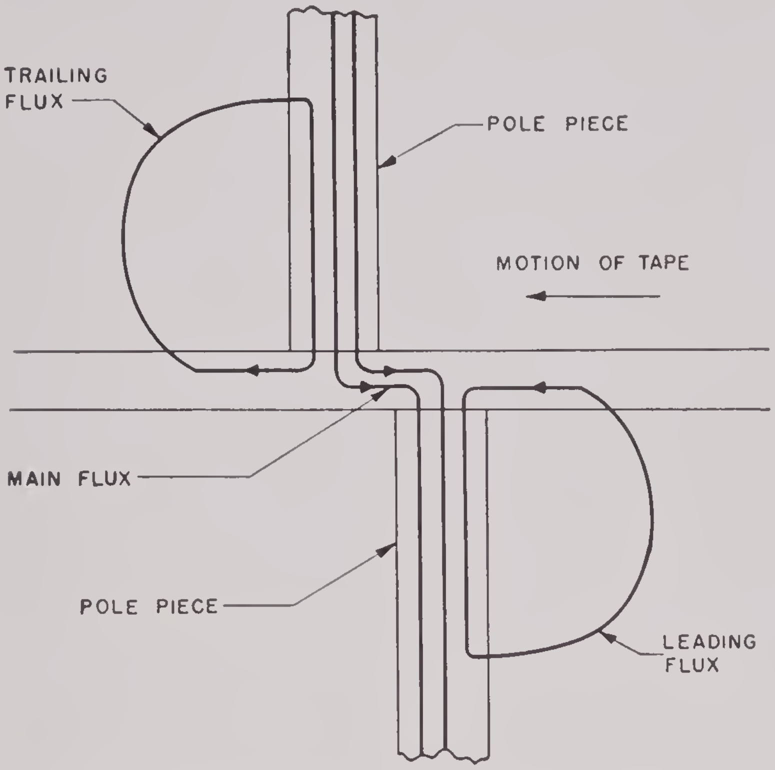

FIGURE 6. Pole and flux configuration for longitudinal recording—early method.

a result of saturation of the tape when passing a d-c obliterating magnetic circuit, or a neutral state, which can be obtained by using a-c obliteration.

If d-c obliteration is used, the tape leaves the obliterating head in a condition determined by the magnetic remanence after saturation. To allow proper recording of the a-c intelligence signal following the obliteration

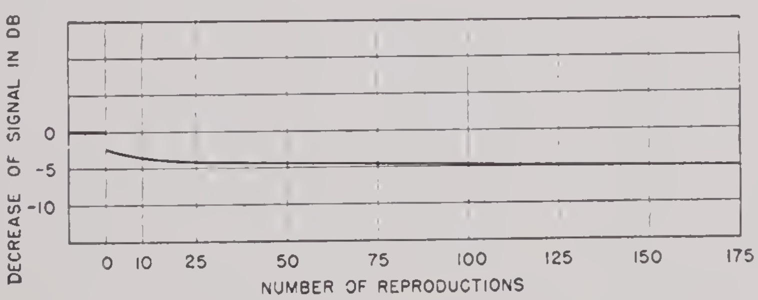

FIGURE 7. Decrease of signal versus number of reproductions.

process, it is necessary to superimpose the signal current on a d-c polarizing current, or bias current, to produce a unidirectional pulsating magnetizing force between the pole pieces so directed that it has a tendency to demagnetize the tape from its remanent magnetic state. This system of recording thus employs d-c obliteration and d-c biasing (pure d-c system).

Where a-c obliteration and a-c biasing (pure a-c system) are used, high-frequency currents are supplied to the obliterating head as the tape passes. A-c obliteration should leave the tape or wire in its neutral or demagnetized state. To achieve this, a field with a peak value sufficient to saturate the carrier, and gradually decaying along the carrier axis, should be generated. In practice a normal recording head is utilized as an obliterating head, but the field decay along the axis is too abrupt. Consequently, some recording of the obliterating frequency occurs, but the amplitude of this recording may be kept very small by choosing an obliterating frequency whose recorded wavelength is smaller than the effective gap width of the recording head. This method has proved quite satisfactory for most practical applications.

Gap Width

Gap width and effective gap width are terms peculiar to magnetic recording. The actual gap width of a given magnetic recording head is the physical distance between the edges of the two pole pieces, measured parallel to the carrier axis. The effective gap width is larger than this, and is determined by the field distribution over an incremental length of the carrier influenced by the recording head at any particular instant of time. Ideally, the field distribution over the length of the increment should be uniform, and sharply defined, i.e., it should be rectangular in shape, and limited to the dimensions of the actual gap noted above. Because of magnetic leakage the shape is never rectangular, but decreases gradually on either side of a maximum. The width of the corresponding "effective" rectangle is somewhat larger than the actual gap width, and represents the effective gap width.

The d-c biasing and obliterating method described allows recording on the essentially straight portion of the hysteresis loop of the carrier material. A-c biasing with a-c obliterating utilizes the artificially straightened center portion of the normal magnetization curve.[17] The a-c bias and obliterating system is somewhat similar to the effect obtained in the operation of a push-pull amplifier, wherein the

curved tube characteristics are combined in the positive and negative excursions of the signal to produce an overall straight line transfer characteristic between the applied grid signal and the output signal. In the magnetic case,

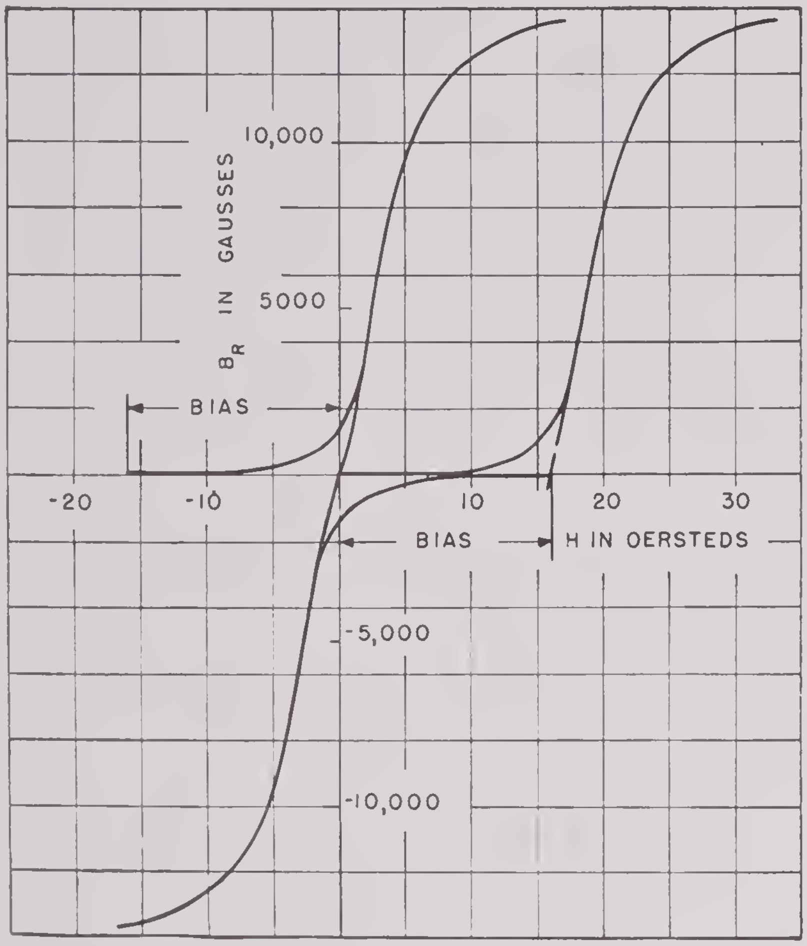

FIGURE 8. Determination of correct bias field and construction of overall magnetic transfer characteristic.

the positive and negative portions of the normal magnetization curve are shifted in the proper directions by the applied bias field, so that the signal superimposed on this bias field (not modulating it, but adding to it) sees the transfer characteristic to the flux distribution in the carrier as a straight line rather than a curved line. (See Figure 8.)

Either of the two methods leads to essentially similar frequency-response curves; the a-c method, however, offers a higher signal-to-noise ratio, usually about 5 to 8 db better, because the neutralized signal carrier, theoretically, cannot generate any noise voltage in the reproducing head.

It is also possible to combine the pure d-c or pure a-c methods, by using d-c obliteration and a-c biasing, either adding the signal to the a-c bias, or using the signal to modulate the a-c bias. The magnetic status of the carrier after it leaves the recording head will correspond to the crest value of one envelope of the bias-plus-signal signal, the other envelope merely tending to saturate further an already saturated carrier. Again, these conditions obtain when the effective gap width is greater than the biasing wavelength. Figure 9 illustrates the mechanism explained. This particular method has not been widely used, as the pure a-c method offers signal-to-noise ratio advantages, while the pure d-c method offers simplicity advantages.

3.4.4 Recording Materials

The initial development work on the MTR indicated that the use of an endless carrier was desirable. This meant that the ends of the tape or wire had to be joined. Such a joint produces a magnetic discontinuity, which may produce a signal which will completely obliterate, or at least seriously distort, the transient being studied. It therefore appeared desirable to investigate the possibility of plating

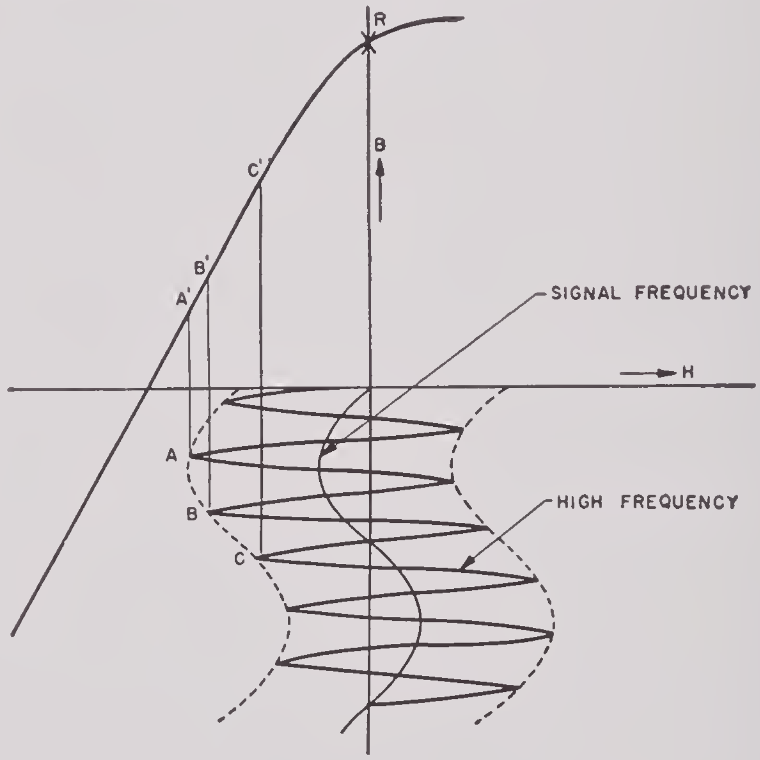

FIGURE 9. A-c bias, d-c obliteration conditions.

a nonmagnetic base with a magnetic layer to serve as the actual signal carrier, such plating, or coating, to be applied after the joining of the carrier, to reduce or eliminate the effect of the joint. Although this idea appeared feasible, it was not incorporated in the MTR as finally constructed, since plating technique, and some factors governing magnetic

behavior of platings, had not been worked out at the time. The initial work on platings indicated that other advantages could be expected from a thin magnetic layer beside the elimination of joints, etc. Thus, as described later in this report, considerable work was done on the development of new magnetic recording media along the lines of thin magnetic layers produced by various means.

3.1.5 Magnetic Transient Recorder

The MTR utilized a highly polished steel tape, about 3x120 mils, operating at a speed of 35 ft per second, giving a total recording time of 20 to 40 milliseconds, with the length of tape supplied. Signal-to-noise ratios of the order of 35 db were obtained, with frequency response from 800 to 30,000 c. Phase shift was held to a minimum by an interesting process described later in this report. The response and signal-to-noise ratios were obtained by the use of the pure a-c system, proper tape speeds, recording- and reproducing-head gap widths, and proper head materials and assemblies. It was found that two 0.007-in. transformer iron strips utilized as a laminated recording head, with two dimensionally similar Mu-metal strips as a reproducing head, gave good results. Although other types of heads, known as ring heads (see Section 3.5.2) were developed during the investigation, primarily for use with plated materials, they were not used in this particular instrument, sufficient data not having been accumulated at the time.

Phase-Shift Elimination

Phase-shift elimination was accomplished by a re-recording process. Though it may be possible to design a network which will provide a phase-shift compensation without serious amplitude distortion, the re-recording method described below is considerably simpler, and serves the purpose.

Let us assume that the recording head and the recording amplifier form a unity having an unknown time delay L which is a function of frequency and that the reproducing head and its associated amplifier have a time delay N which is also a function of frequency. The overall time delay between the input terminals and the output terminals of the equipment is then given by the sum $L + N + T$. T is the time delay introduced by the distance between the recording and reproducing heads, which is independent of frequency and therefore can be neglected. If, after recording, the direction of the carrier motion is reversed, for playback, the overall time delay will be $N - L$. The minus sign associated with L comes about since the most delayed portions of the signal become the most advanced due to the change of direction. The signal derived from the reproducing head is now backwards. By re-recording this signal obtained from the reversed carrier on to another carrier through the identical amplifier and recording head, we obtain on the second carrier recording with time delay N,

$$\underbrace{(N - L)}_{\text{First recording and playback}} + \underbrace{L}_{\text{Second recording}} = N$$

If this re-recorded carrier is reversed, we obtain a time delay $N - N = 0$ at the output terminals, and the signal is no longer backwards.

Oscillographic proofs of this method are contained in Figure 10. Part 1 shows the signal at the input terminals of the recording amplifier. Part 2 shows the signal at the recording head. Phase shift occasioned by the amplifier and head is present. Part 3 shows the reproduced signal after reversal of the carrier, as seen at the output terminals of the reproducing amplifier. Part 4 shows the recording-head signal while making the second recording. Part 5 is the signal obtained from the reproducing amplifier after the second and final carrier reversal. Without the phase-shift compensation method employed, the signal shown in Part 6 is obtained. Some low-frequency disturbances obscure the results somewhat, but it can be seen that almost complete phase-shift cancellation has been effected. Re-recording has one disadvantage, in that it reduces the overall signal-to-noise ratio which can be realized. Otherwise, it appears to be satisfactory as a means of phase compensation.

MTR Construction Details

The MTR as finally constructed is briefly described below, including the phase-shift cancellation method outlined above. At the time of the construction of this unit it was apparent that considerable additional work would have

to be done to improve characteristics of recording media then available. While such work was being carried on, it was decided to construct at the same time a unit using a steel tape, without plating but with soldered or welded joints to allow the use of a continuous loop. The basic configuration of the instrument circuit is shown in Figure 11. Since a re-recording process is necessary to eliminate phase shift, two independent recording channels were supplied. Initially, no re-recording was in process, allowing both channels to be used for

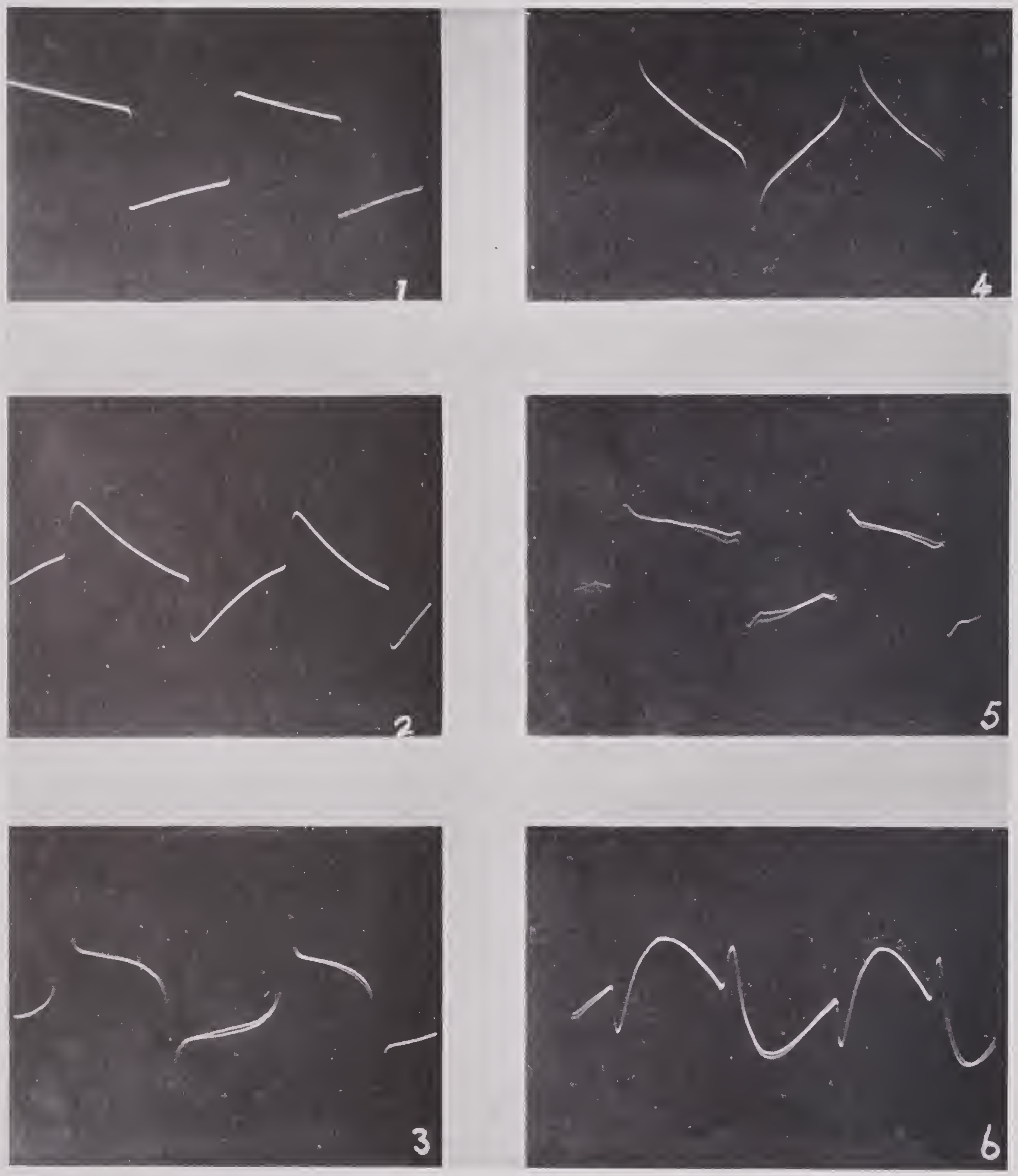

FIGURE 10. Phase shift correction by re-recording.

recording the original transient. This aids in obtaining a record from at least one of the recording channels where the transient from the tape joint does not seriously interfere with the transient under study. Each tape loop is designed to accept a recording having a duration of about 1/50 second, although one tape cycle lasts for 1/25 second. The unit as finally constructed had a response from somewhat below 800 to over 30,000 c, with a signal-to-noise ratio of about 30 db, after re-recording.

Figure 11 shows the operation of the system as used to make the initial recording. The transient signal is fed to an input amplifier and trigger circuit, which controls the operation of the recording amplifier and obliterating head. Thus on receipt of a signal, obliteration stops, the signal is recorded on both channels, and is ready for choice of the best record, and re-recording. A circuit called a *click remover* [CR], somewhat similar to noise limiter circuits used in communications radio receivers, is applied to the chosen record in such a manner that the loop-joint click transient is removed from the channel prior to re-recording on the now obliterated second channel. Since the position of the transient on the chosen recording may be determined with reference to the joint in both tapes, re-recording can be made without the second tape joint being in a position to interfere with the signal transient. The CR is used on final playback, following the second reversal of tape motion, to prevent it from detracting from the observation of the initial transient on the cathode-ray oscilloscope.

The MTR is thus reasonably free of spurious disturbances, and provides reasonable response, phase, and noise characteristics to allow its use for many problems. As a result of later work in the field of magnetic recording media (ER, PCT), more adequate characteristics could be obtained, but work under OSRD was discontinued before such a redesign and application were possible.

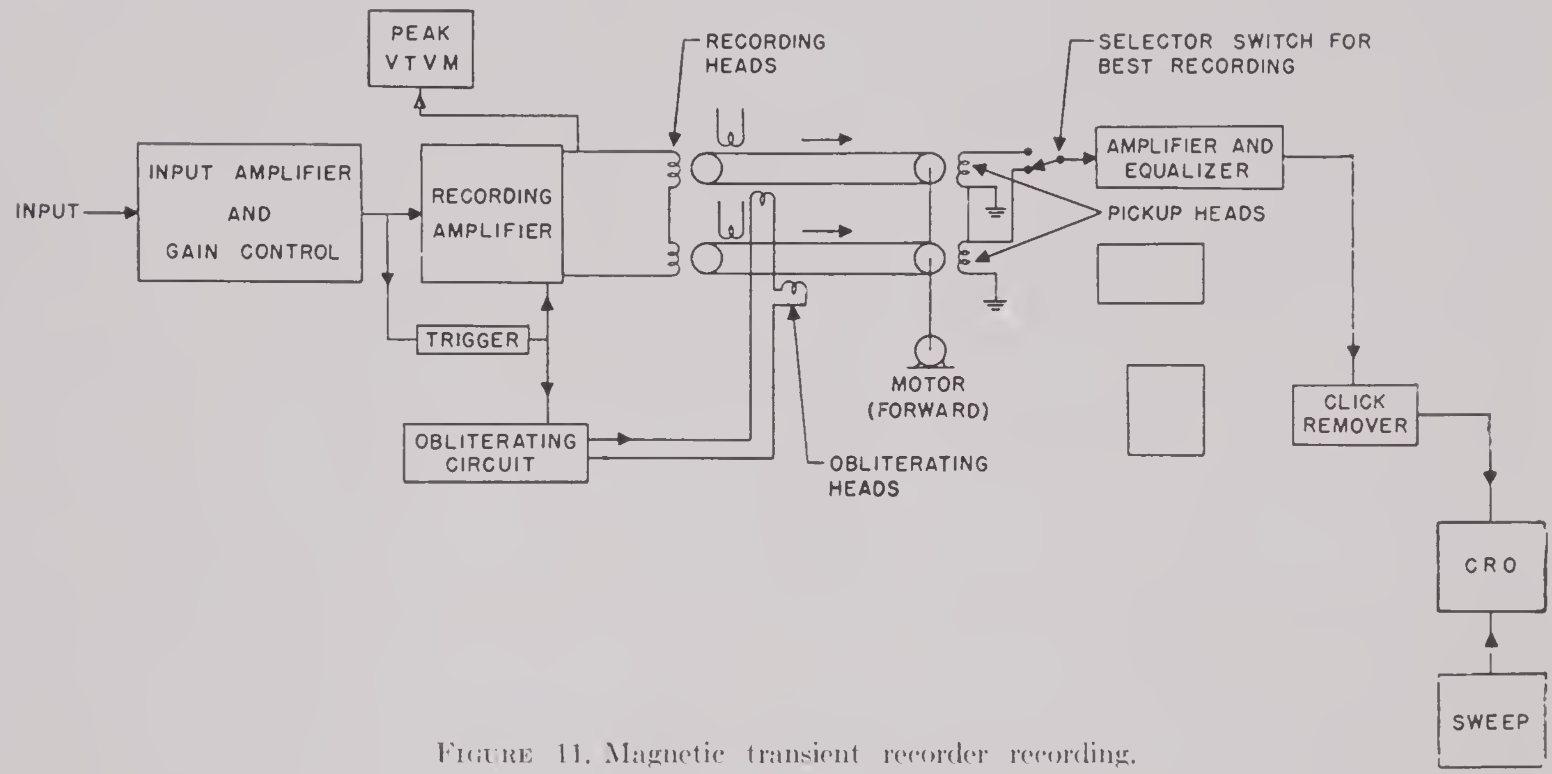

Figure 11. Magnetic transient recorder recording.

3.5 MAGNETIC RECORDING MEDIA

3.5.1 Military Requirements

Initially there were no military requirements established for the development program on *magnetic recording media* [MRM]. Studies of MRM were initiated as a result of difficulties encountered in the development of the MTR. It had been hoped to eliminate joint transients (clicks) in the MTR tapes by plating a nonmagnetic loop with a continuous magnetic plating. Later work on the development of MRM was carried out under a directive from Army Air Forces.[c] The main objective of this directive was to obtain MRM which would

[c] SC-111

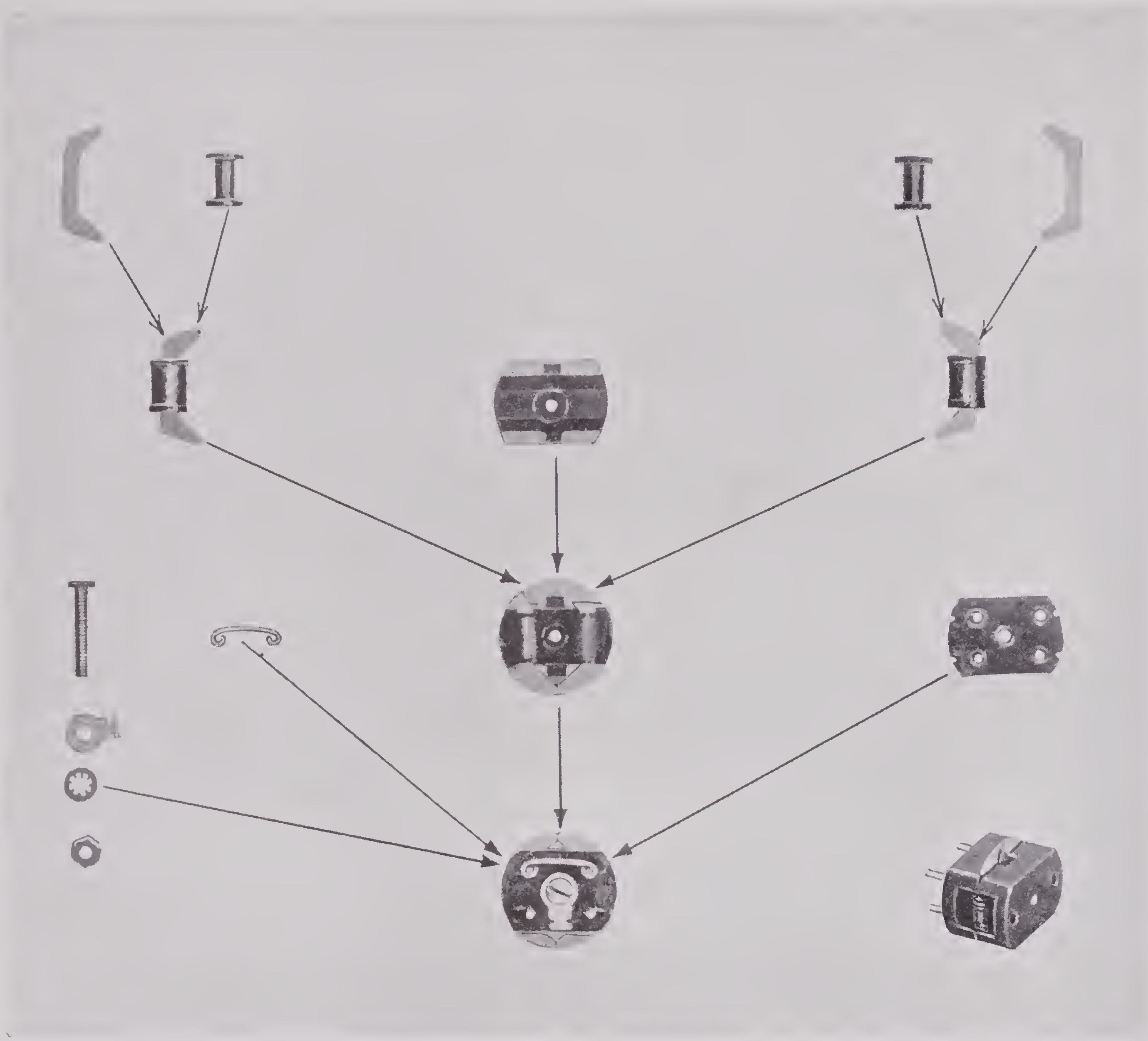

FIGURE 12. Assembly of head cartridge (actual size).

allow adequate performance in airborne apparatus, yet require less storage space than MRM available at that time.

3.5.2 Ring Heads

It was found from plated-tape studies that a design of special recording and reproducing heads, known as ring heads [RH] was necessary. The standard magnetic head used for longitudinal recording uses two pole pieces on opposite faces of the tape, focusing the field within an area limited on both ends by the slightly offset pole pieces. (See Figure 6.) These pole pieces do not produce the same effect with a plated tape, since between the two magnetic layers on the faces of the tape, a nonmagnetic portion is sandwiched, which encourages undesirable leakage paths for the recording flux. The RH design is such as to concentrate the flux in the magnetic layer nearest to it, making a tape plated on one side all that is necessary, and eliminating the leakage path effects mentioned.

Figures 12 and 13 illustrate the design and construction of one of the later models of this head. The head is essentially a ring with a small, carefully controlled air gap at the point of contact with the magnetic layer of the tape used as a signal carrier. A second air gap is provided on the opposite side of the ring. While

the tape actually contacts a considerable portion of the ring on either side of the gap during normal operation, the effective slit width is always determined by the air gap itself, since the reluctance of the ring material is so much lower than that of the tape that practically no flux leaks across to the tape except at the air gap.

It should be emphasized that RH are inferior to standard heads when used with standard steel recording tape, probably due to the greater thickness of the magnetic material of the tape which allows more spreading of the flux and hence less definition for high frequencies. However, the RH have definite advantages for plated or coated tapes, where the magnetic material is thin. All tests on ER or PCT were made with ring heads similar to that described. Some plating tests carried out on disks did not use RH, but used modified heads of standard design.

3.5.3 Early Plating Developments

While some of the earliest plating tests were made on a nonmagnetic metallic tape, beryllium-copper, these tests did not prove very satisfactory, although hope for future developments led to a continuation of work on tapes. To facilitate early plating tests and analysis of results, as well as to supply recording signal

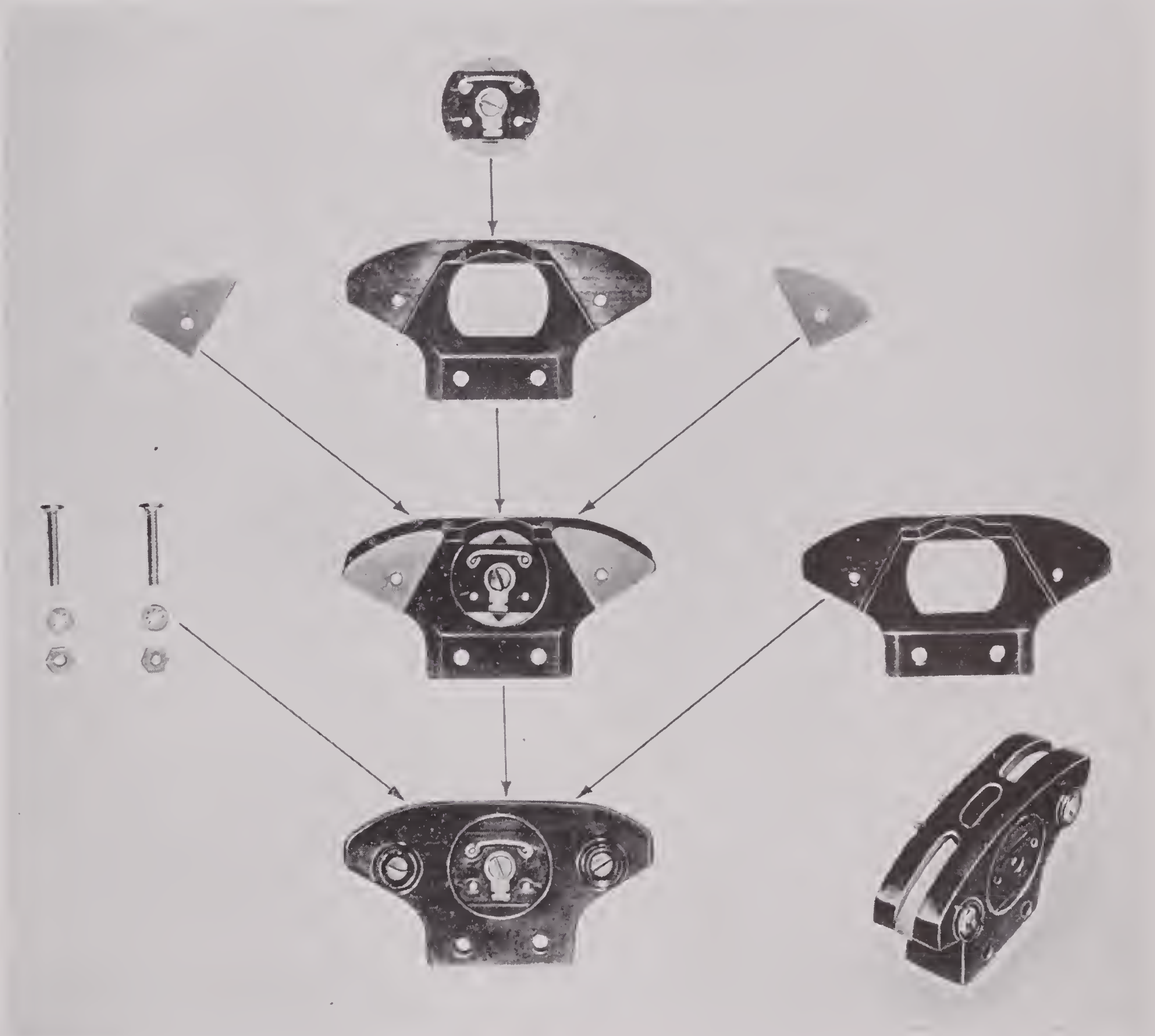

FIGURE 13. Assembly of recording head (actual size).

carriers for then available apparatus in use by the Services, it was decided to carry out tests on the plating of nonmagnetic disks, for comparison with the tool-steel disks then in use. The disks were about 4 in. in diameter and 3/16 in. thick, after machining and initial polishing. Several different materials were used as a base to allow study of the effects of heat treatment on the magnetic plating without distortion of the base itself. Prior to plating, all disks were carefully polished. Even after such polishing, it was found that variations in background noise, predominantly low-frequency effects, existed. This was found to depend on the uniformity of the plating crystallization, which in turn was dependent upon the uniformity in crystalline structure of the base material.

During initial tests it became apparent that the unrelieved strains present in a magnetic plating were directly related to its magnetic characteristics, and that heat treatment which tended to reduce these strains would reduce the quality of the plating for magnetic recording.

An iron-cobalt alloy was chosen for the magnetic film, in a ratio of 35 per cent Co to 65 per cent Fe, after numerous trials. This combination appeared to have the best signal-to-noise ratio of the various compositions tried at that time.

Studies were made of optimum plating solutions, current densities, *p*H values, plating temperatures, and mechanical arrangements of plating apparatus. The general arrangements are briefly noted here.

1. The plating solution consisted of:

360 g	Ferrous chloride
180 g	Calcium chloride
150 g	Cobalt chloride
Water to make	1 liter.

2. The anode used was Armco iron.
3. The current density direct current was about 20 amp per square foot.
4. The *p*H of the solution was 1.5.
5. The plating temperature was 70 C.

It was found that higher current densities, or lower *p*H values, caused pitting of the plating. To prevent the plating from following the crystalline pattern of the base material, the disk was rotated while being plated. A number of thin layers, about 4, each about 0.0002 in., were applied, each being polished prior to application of the next layer.

A nonmagnetic base material having a fine grain structure was desired. Brass containing 70 per cent copper, 29½ per cent zinc, and ½ per cent phosphorus, heat treated at 800 F was selected.

Since the plating as deposited had substantial strains created in the magnetic layer, its characteristics appeared adequate without further treatment after deposition.

A signal-to-noise ratio of 40 db, as compared to 20 db obtained with tool-steel disks under identical conditions, was obtained. An oscillographic comparison of the difference in signal-to-noise ratio is shown in Figure 14. As a result of this initial success it was decided to expand the program on the study of MRM to allow a comprehensive study of various types and methods of plating and coating tapes, in the hope of obtaining materials superior, from the standpoint of response and signal-to-noise ratio, to the then available materials.

3.5.4 Extended Studies

In addition to the advantages realized in plated signal carriers on disks, outlined above, it was felt desirable to carry out extensive work on the development of easily produced tape or ribbon recording materials, along similar lines, even if they did not prove markedly superior to previously available homogeneous materials, such as tungsten steel tape. This decision was based on the fact that many of these materials were imported prior to the start of the war, and became increasingly difficult to obtain as the war progressed. It appeared that the deposition of thin magnetic layers on nonmagnetic bases might offer a more economical solution, from the standpoint of availability of materials, and necessary manufacturing man-hours, than would the development of materials duplicating those previously imported.

General Methods

With these points in mind, several methods for deposition of thin magnetic layers were considered. They included: (1) electroplating, (2) evaporation, (3) suspension of fine parti-

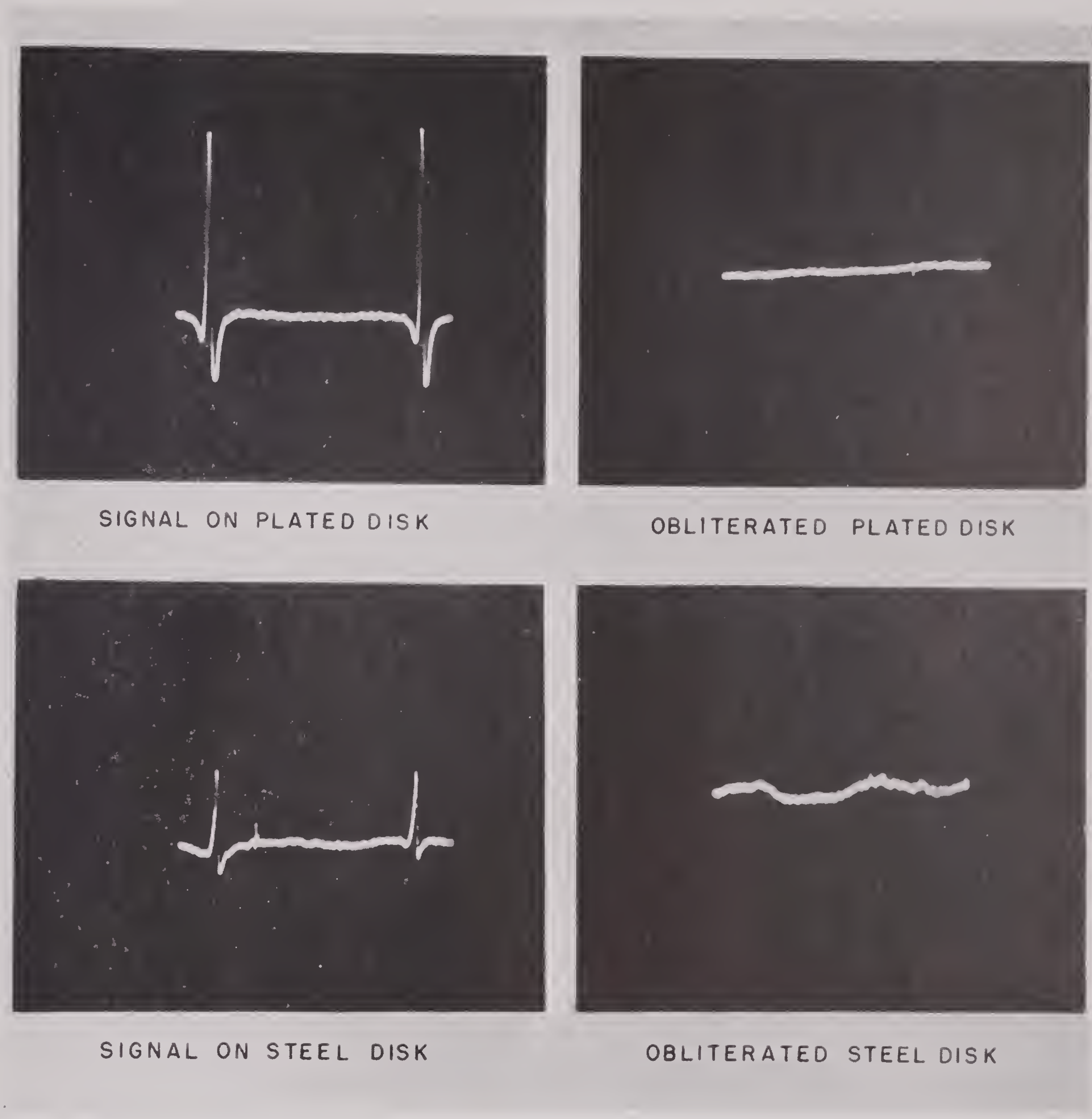

FIGURE 14. Signal to-noise ratios for plated disk and tool-steel disk.

cles in a supporting medium, applied to a suitable base, (4) spraying, and (5) cathode sputtering.

Of these methods, the first three were investigated with considerable care but the two latter were disregarded since the other methods appeared to offer greater possibilities of an early solution.

Previous experiments of electroplating on disks served as a basis for further work in this field. The selection of metals used in electroplating is limited by the plating possibilities of the metals either alone or in alloyed form.

Evaporation is the process of condensing the vapor from molten metal onto a base material in vacuum. The selection of metals to be used is limited by the partial vapor pressures of the metals comprising the melt.

The suspension method provides a wide

choice of magnetic materials, since the material is ground and suspended in a supporting medium before it is coated onto the base material. This process does not depend upon as many physical and chemical properties of the material as is the case with the other methods.

3.5.5 Plating

Initial plating tests were made on tapes of beryllium copper or manganese steel 0.002 to 0.003 in. thick and about 0.014 in. wide. As stated, these tests were an extension of work on plated disks. Early results obtained from the tape-plating tests were discouraging, but led to the discovery of interesting data serving to confirm the fact that internal stresses within the magnetic layers were directly related to the performance of the magnetic medium. Signals recorded on these early tapes would gradually decay. The coercive force of the magnetic layer on these tapes was considerably lower than the coercive force of the same material when deposited on disks. It was suspected that the tape was not sufficiently rigid to withstand the considerable forces developed by the stresses within the plated film, without being distorted and thus permitting their relief. The magnitude of these forces was conclusively indicated by the tape buckling badly when only one side was plated.

At the time, a solution appeared difficult. However, further studies indicated that there were advantages to an extremely thin signal carrier from the standpoint of penetration effect. This change to a somewhat thinner carrier, plus a change in plating technique, wherein a-c and d-c currents were superimposed during the plating procedure, finally allowed the production of a satisfactory tape.

Since some 300 tapes and 2,000 short strips were plated during the course of the investigation, it is felt that a brief discussion of the main types of platings studied, some statements on the techniques, and an indication of results obtained on the best platings will suffice.

On the basis of data available in the literature and trade, the use of alternating current superimposed on direct current as a plating current seemed desirable because of better appearance and adherence of the plating. In the course of the investigations, it was observed that the coercive force of almost all the ferromagnetic platings increased considerably when alternating current was superimposed on the direct current during the plating process. It is significant that this effect occurs only when the peak value of the alternating current exceeds the direct current; i.e., when the cathode becomes temporarily anodic during each a-c cycle. The effect also increases, up to a certain limit, with the duration of the current reversal, i.e., with increasing a-c to d-c ratio. Consideration of this and other data leads to the suggestion that occluded gases (particularly oxygen) or their metal compounds, serving as stress centers in a manner similar to that of dispersion or precipitation hardening of alloys, increase the trapped stresses within the plated material and thus increase the coercive force. A-c—d-c plating was used in all final plating tests, and the best results were obtained with it.

Platings of the following materials were tested: nickel, iron, cobalt-iron, nickel-iron, cobalt-nickel-iron, cobalt-nickel, iron-cobalt-chromium, and iron-cobalt-molybdenum.

Values of coercive force (H_c) and remanence (B_r) were measured with a B-H meter developed for this purpose, in which the hysteresis curve of the material was automatically plotted on a cathode-ray tube, whose screen was calibrated in oersteds for H_c and gausses for B_r.

Temperature, pH, current density, and a-c to d-c ratios were noted and controlled. Numerous types of plating baths, to give various crystalline structures, and alloy compositions were employed. The addition of boric acid (H_3BO_3) to many of the plating solutions improved both the appearance and the adherence of the coating. In general, especially in the case of plating from Fe, Ni, and Co, the chloride solutions of these metals were preferred.

A plating thickness of about 0.0003 in. was used in most cases, since any increase in the plating thickness above this value does not improve the values of B_r or H_c. As explained previously, thin signal carriers offer advantages, at least when used with RH, from the standpoint of penetration effects at high frequencies.

As a result of these studies, a plated tape, utilizing a base material of phosphor bronze,

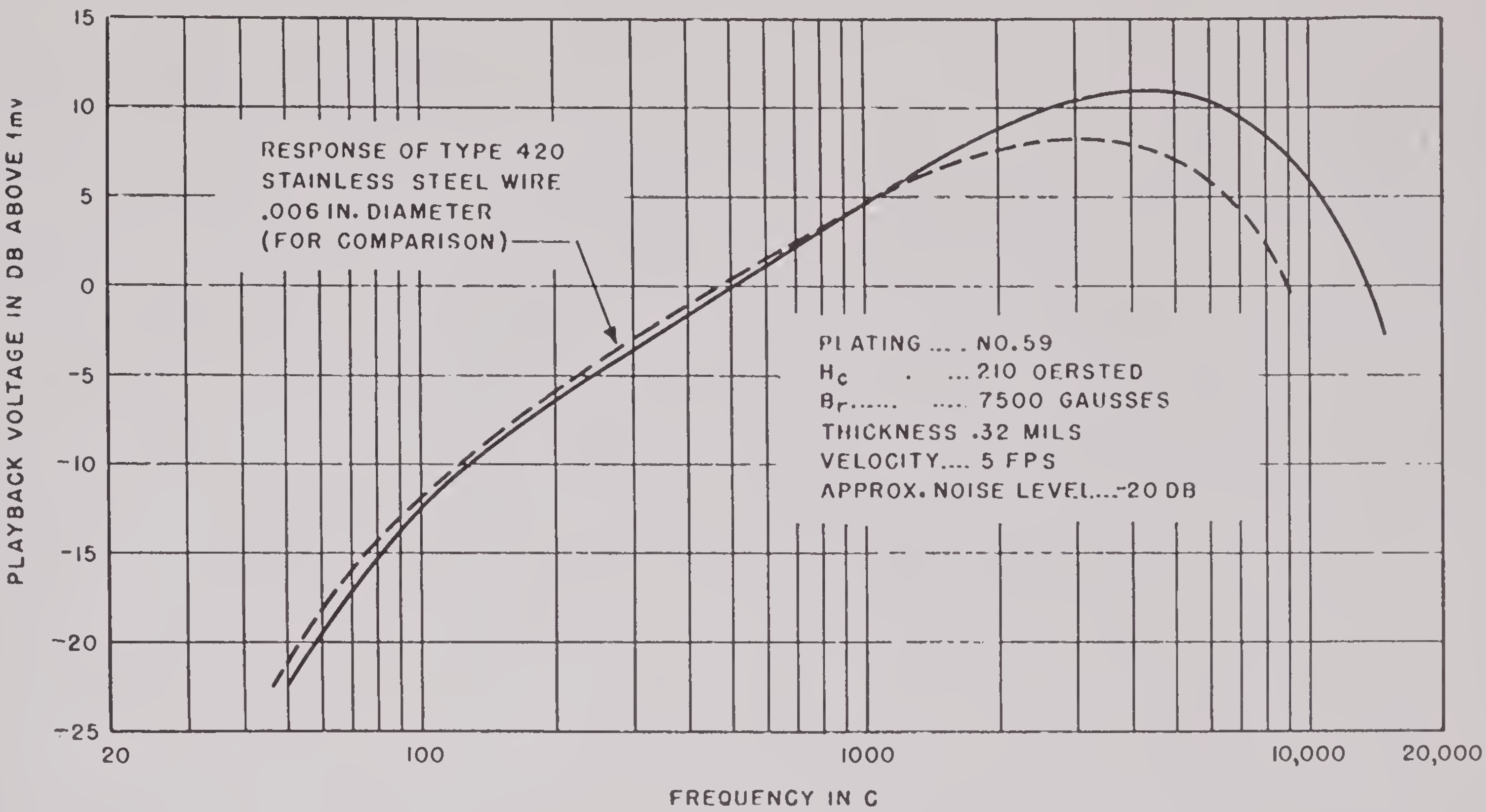

FIGURE 15. Frequency response of plated tape No. 59.

was produced, with good magnetic recording characteristics, adequate mechanical strength and wear resistance, and capable of easy production.[9] The tape was identified as No. 59. Its characteristics are as follows:

Response* signal-to-noise ratio	See Figure 15
Thickness	0.002 in.
Width	0.014 in.
Breaking strength† (plated)	5 lb
Plating thickness	0.00032 in. (one side only)
Plating composition	80 per cent cobalt 20 per cent nickel
Coercive force, H_c	210 oersteds
Remanence, B_r	7,500 gausses

* It is interesting to note that the velocity of tape No. 59 can be reduced 30 to 40 per cent below the velocity of frequently used steel wire, and still produce the same response.

† The unplated strength is about 3 lb. Thus the plating layer exhibits an apparent strength of about 300,000 lb per sq in., the same order of magnitude as found in homogeneous materials having similar magnetic properties, produced by costly drawing, rolling, etc.

Data on plating technique used to obtain this tape are of interest and illustrate a typical set of conditions used in these studies.

Solution: 50 grams cobalt (as a chloride) } per liter of solution
50 grams nickel (as a chloride)
25 grams boric acid

Temperature: 70 C.

pH: 4.7

A-c/d-c: 350/100 (i.e., 350 amp a-c, 60 c per sq ft. 100 amp d-c per sq ft, currents superimposed)

A continuous plating apparatus was constructed to plate long lengths of tape, following continuous automatic cleaning by a solution of trichlorethylene as a degreaser, followed by a hot solution of NaOH and NaCN. The plating unit is shown in Figure 16.

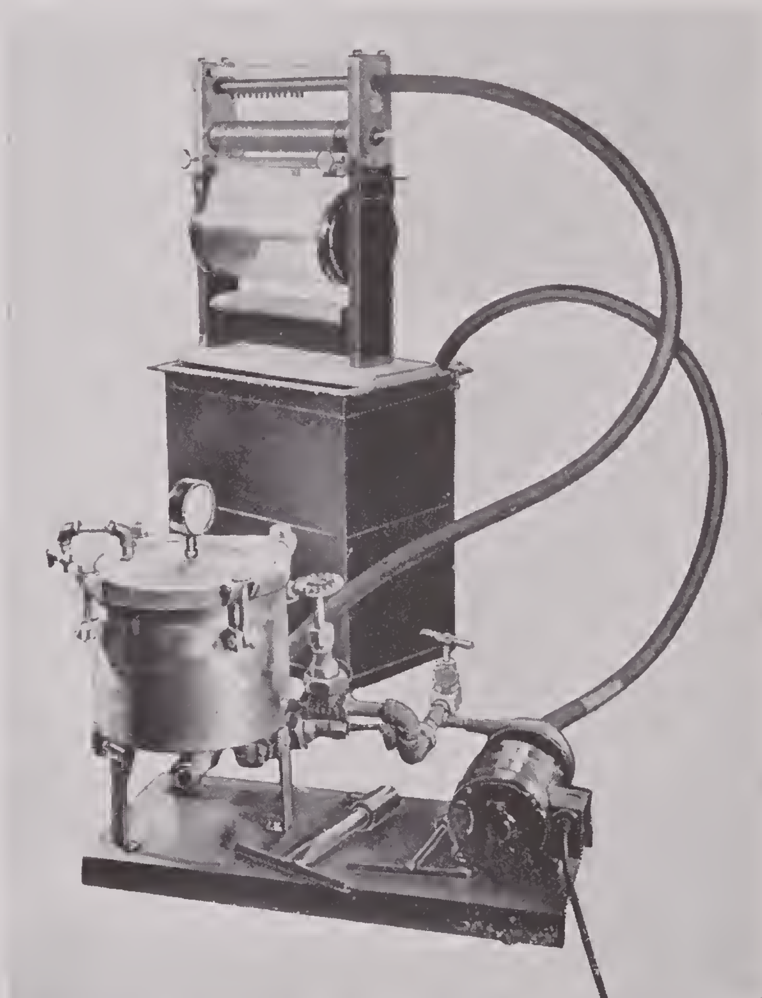

FIGURE 16. Improved plating unit, showing filter and pump for dripping system.

3.5.6

Evaporation

Equipment

The evaporation of metal can be carried out in a satisfactory manner only at pressures of 10^{-4} to 10^{-5} mm of Hg. Apparatus capable of attaining these pressures in a reasonable time was constructed, with provisions for pressure measurement. Adequate room was provided within the evacuated chamber for electrical and mechanical facilities needed to carry out experiments. The chamber consisted of an 18-in. diameter bell jar with a steel base plate, an oil diffusion pump, and auxiliary mechanical pumps.

Power was supplied to the evaporation sources through a Variac-controlled transformer. Provisions were also made to produce a glow discharge in the bell jar during the pumping, since it has been reported that such a discharge cleans up the various surfaces in the chamber and thus aids in attaining a high-vacuum. P_2O_5 driers were also incorporated in the system.

Materials Studied

While it had been hoped that some work could be done on the evaporation of Fe-Co-Mo melts, theoretical considerations of the vapor pressures of the various constituents made it appear that the evaporation of appreciable Mo from such a melt would be difficult, if not impossible. Therefore it was decided to concentrate on melts of Fe-Co, and possibly certain Alnico compositions. Since heat treatment of Fe-Co alloys cannot be expected to cause significant magnetic hardening (increase in internal stresses), the stresses obtained in the evaporation process itself were depended upon for these characteristics.

Methods

The ordinary method of evaporation of a metal is to place the metal on an electrically heated filament of refractory metal such as W, Mo, Ta, etc. Although these materials can be used at high temperatures, it was found that Fe-Co in solid-liquid equilibrium with these materials forms an alloy rich in Fe or Co, melting at considerably lower temperature, about 1500 C. Since this change will cause failure of a filament used in evaporation techniques, new techniques of evaporation from such filaments, and from special crucibles, had to be developed. It was found that filaments of W, plated with Fe-Co, where the mass ratio of Fe-Co to W was kept below the value of about 0.2, would allow successful evaporation from filaments, since the alloying effects were confined to the filament surface. The thickness of layers that could be evaporated by this method was restricted to about 3×10^{-5} in., because of the limited ratio of Fe-Co to W.

To overcome this restriction, crucibles of BeO, formed over a heating element of W, 25 turns of 25-mil wire, were developed.[8] These crucibles held a charge of 5 g, sufficient to deposit a layer about 3×10^{-4} in. on a surface 15 cm away. Evaporation rates of about ½ gram per hour were obtained at temperatures of 1550 C.

Actual evaporation took place onto disks similar to those used in the initial plating experiments, i.e., about 4 in. in diameter. Various base materials and surface treatments were used to improve the adherence and surface of the evaporated film.

Measurements of the magnetic properties and thicknesses were made with the *B-H* meter[8] previously mentioned.

Variables

Most experiments were made with melts which produced an alloy of 35 per cent Co, 65 per cent Fe. The following factors were studied for their effect on coercive force and remanence.

1. Source of specimen distance.
2. Nature of backing, or base, material.
3. Composite backings.
4. Rate of evaporation.

It was found that a great improvement in both H_c and B_r is obtained when the source-to-specimen distance is large. This is caused by the fact that at short distances, the backing material, and the evaporated film, are at high temperature, due to the radiant energy received from the source. At greater distances, lower temperatures obtain. Under these conditions, less annealing effect occurs, so that the internal stress regions are produced and maintained more readily. This produces better val-

ues of H_c and B_r. The adherence of the evaporated film to the base material is also dependent upon unrelieved stresses, as well as surface conditions, etc. Thus, while great source-to-specimen distances produced better films from a magnetic standpoint, the increased stresses caused peeling of the film to occur much earlier in the process, so that only very thin layers, from 1 to 10×10^{-5} in. thick, would adhere.

Numerous backing materials, and various methods of surface finishing and cleaning were studied. An upper limit of 10×10^{-6} in. for the evaporated films was obtained, after which peeling occurred regardless of the backing materials or techniques used, unless the backing material was at a high temperature, which allows stress relief and produces unfavorable magnetic properties.

Some composite backings were tried, using intermediate layers of chromium, aluminum, copper, and chromium-aluminum. While some reasonably good results were obtained with Cr-Al intermediate layers on a glass base, with the usual Fe-Co evaporation layer, the thickness produced, about 9×10^{-5} in., was not fully adequate for magnetic recording.

Increases in the rate of evaporation were found to improve the magnetic characteristics of the films, but reduce the adherent thickness, as mentioned before. Values of H_c as high as 150 oersteds, and B_r of 23,000 gausses, were obtained.

Conclusions

The coercive force of the evaporated layer has been shown to be relatively high at low backing material temperatures and high evaporation rates. Adherent thicknesses were shown to be low for materials with reasonable magnetic properties, apparently caused by associated internal stresses. It is probable that Fe-Co evaporated films with a coercive force of about 80 oersteds and a thickness of 2×10^{-4} in. might be produced by the use of composite backings. Other alloys do not appear favorable for use in the evaporation process. Wear resistance and production problems, in addition to the somewhat inferior magnetic results obtained, seem to discourage the use of this material, especially in view of plated and PCT characteristics.

3.5.7 Powder-Coated Tapes

General

The object of this research was to develop a tape consisting of a nonmagnetic backing having one surface coated with a magnetic powder, the performance of which would be comparable with that of homogeneous recording media. A tape was developed whose performance exceeds that of present available homogeneous media.

On the basis of cost, bulk storage, mechanical strength and wear characteristics, it was decided to concentrate this portion of the program on the development of a suitable magnetic coating to be applied to one side of a cellulose acetate tape 0.25 in. wide, and about 0.0015 in. thick.

Early work included tests on various magnetic powders, and methods of application to tapes. Among the powders tested, and some of the values of H_c obtained with the B-H meter, were the following:

Material	H_c in oersteds
Red Magnaflux powder	50
Grey Magnaflux powder	20
Martensitic steel No. 190	55
White iron powder	50
Alnico powder No. 1*	120
Alnico 2A2-6a	80 (on cellulose)
Alnico 2A2-7a	80 (on Saran)
Alnico 2A3-7a	84 (on Saran)
Alnico 2A3-7a	80 (on cellulose)
Magnetite, Fe_3O_4	100-200

* The various designations for the Alnico powders identify sources and particle sizes.[8]

Values of remanence B_r were extremely low for the magnetite. Accordingly, the high ratio of coercive-force/remanence made possible the prediction that the material should provide good response characteristics as a magnetic recording medium. Recording tests confirmed this fact.

Application to Tape

Lacquer for application of the magnetite powder to the tape, primarily cellulose acetate, must withstand wide humidity and temperature conditions, adhere to the tape under all these conditions, and be applicable to the tape without softening or weakening it. After several trials, a cellulose acetate lacquer X-6566, which proved entirely satisfactory, was obtained from the Columbus Varnish Company.

Following mixing of the lacquer and magnetite, application may be made by several methods. One method is to pass the paper or plastic over a roll above which is a cell with a knife-edge back. The cell is filled with the lacquer to be applied and the knife edge limits the coating to the desired thickness. Following coating, the material is passed through a drying furnace in a continuous process.

Roller coating may also be used, as may spraying under carefully controlled conditions.

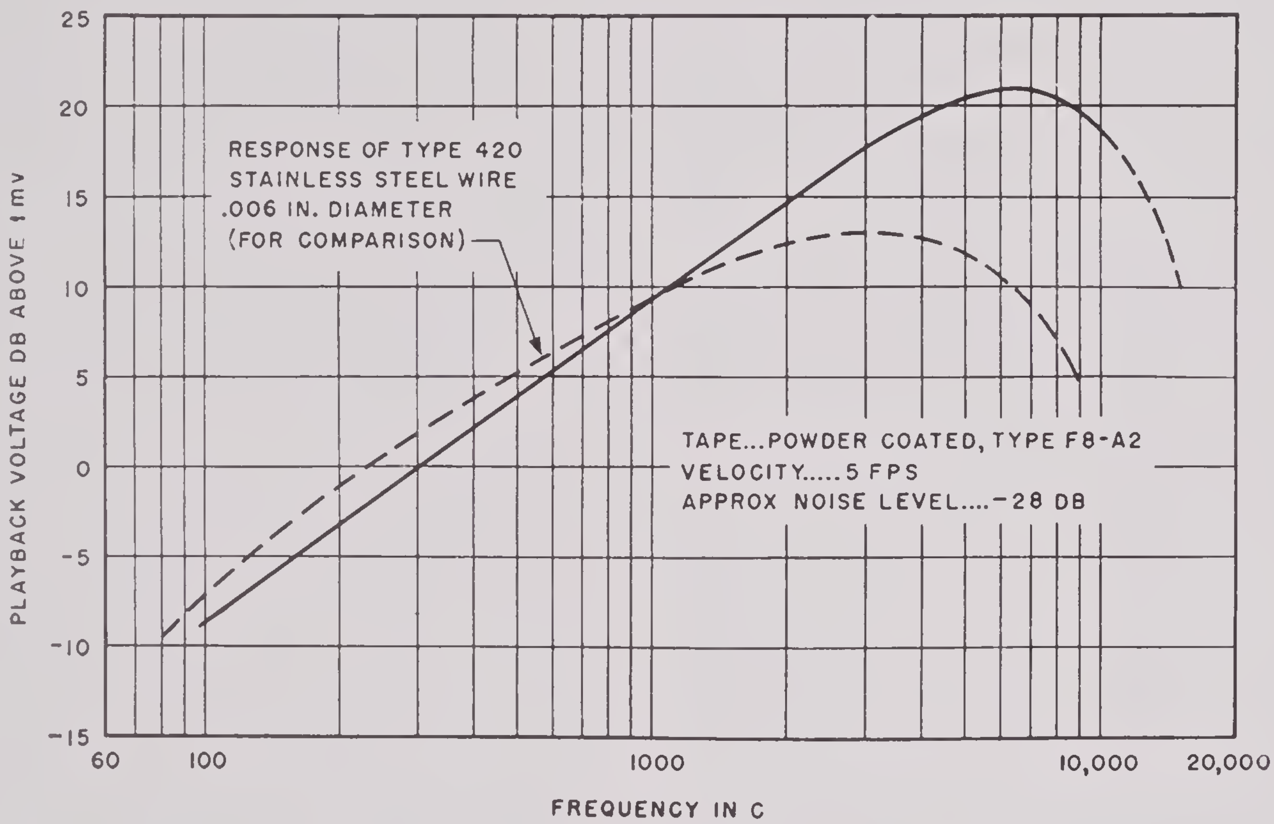

Figure 17. Frequency response of powder-coated tape.

Sources of Magnetite

Magnetite is a naturally occurring mineral, found in relatively high purity and large quantities in New York State. It is also produced synthetically for use as a paint pigment. Such magnetite has a maximum particle size of about 4 microns, and can be obtained at a cost of about 10 cents per pound.[9] It was found that the materials for a mile of this coated tape cost about 50 cents, exclusive of coating cost. A mile of tape will record from 40 to 90 minutes of program with good fidelity and forms a reel about 16 to 18 in. in diameter.

Conclusions — PCT

Magnetite-coated tapes were produced by various contractors in lengths as long as a mile without joints or splices. Both cellulose acetate and paper bases were supplied. The final product had response characteristics as shown in Figure 17 which was obtained with an RH modified to accommodate the PCT. Standard parts were used, obtained from the head shown in Figures 12 and 13, but a sufficient number of laminations was stacked to obtain the required track width for the PCT. In the particular case cemented laminations (amounting to a stack thickness of slightly over 1/8 in.) were used with flat tape guides 1/4 in. wide between the side plates.

The tape characteristics, to summarize, are as follows:

Width	1/4 in.
Thickness	0.0015 in.
H_c	100-200 oersteds
B_r	About 300-500 gausses

The high ratio of H_c to B_r indicates a good response and good signal-to-noise characteristic. This is illustrated in Figure 17.

Production cost and availability of materials and producers are, and should continue to be, extremely favorable.

3.6 CONCLUSION

The development of new and improved magnetic recording media, initiated as a result of

work done on a magnetic transient recorder, has resulted in media capable of equaling or surpassing previously available homogeneous magnetic recording media, in both response and signal-to-noise ratio characteristics. Availability of these media is excellent, based upon ease of production, and convenient sources of necessary materials. Manufacturing and material costs are low, thus making the wide use of such media appear desirable.

The magnetic transient recorder development has shown one of the many possibilities of magnetic recording applied to measurement problems.

Chapter 4

OSCILLOGRAPHS[a]

By *George E. Beggs, Jr.*[b]

4.1 INTRODUCTION

THIS REPORT describes briefly four oscillograph developments under Division 17 of the National Defense Research Committee. Three of these resulted in apparatus for use by the Ordnance Department of the U. S. Army and the Bureau of Ordnance of the U. S. Navy. Apparatus was intended primarily for use at the various proving grounds, for accurate quantitative measurements of such things as blast pressures, trunnion reactions, recoil-cylinder pressures, barrel strains, and muzzle velocities. Such measurements were needed in connection with interior ballistic studies necessary for establishing gun-design principles and data, improvement of projectile and bomb shapes, the development of automatic weapons for aircraft, and the design of aircraft structures to support such weapons.

Since measurements of this type require a wide range of frequencies and amplitudes to be covered by automatic recording apparatus, it was felt desirable to attempt to design and construct several different systems utilizing either cathode-ray tubes or mechanical oscillograph elements recording on photographic media. Accordingly, three contracts were established under the supervision of the NDRC at the request of the War Department.

Project OD-73 was concerned with the development of a multi-element mechanical oscillograph with associated d-c amplifiers, for the simultaneous recording of six channels of information on photographic paper. The work was done by the Hathaway Instrument Company.[1-3]

Project OD-102 was concerned with the development of a three-channel cathode-ray oscillograph with a fourth channel to introduce timing lines. The units were to be adaptable to recording on a drum camera with a frequency response as high as several megacycles, far beyond the range of the mechanical recording oscillograph under Project OD-73. The work was done at Purdue University.[4-7]

Project OD-140 was concerned with the development of a mobile laboratory trailer containing a four-channel recording cathode-ray oscillograph with relatively wide band response, an associated high-speed camera to photograph the traces, and adequate for initiation of auxiliary apparatus operations in the field (i.e., the firing of the gun), for the starting of the recording camera and oscillograph traces, and for the rapid development of the traces for analysis after the records are taken. The work was done by White Research Associates.[8,9]

From the brief description above, it can be seen that the three developments tend to supplement each other in frequency response, versatility, and mobility. All sets of apparatus were completed and delivered to the Aberdeen Proving Ground, Ballistics Research Laboratory. Units developed under OD-140 for similar application were in process of completion in September 1945 at the Dahlgren Proving Ground, by the Bureau of Ordnance, U. S. Navy.

The fourth oscillograph development, under AC-67, was for the purpose of furnishing to the Army Air Forces Proving Ground Command, Eglin Field, Florida, an instrument trailer, the primary function of which was to be the recording of time sequences originating from an airplane in flight and terminating on or near the ground. The recording was to be accomplished by means of recorded impact, sound or light impulses. The work was done by the Shell Oil Company.[10]

4.2 MULTI-ELEMENT OSCILLOGRAPH (OD-73)[1-3]

4.2.1 Military Requirements

The performance requirements and general description of the apparatus were specified in some detail by the Aberdeen Proving Ground.

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[a] OD-73, OD-102, OD-140, AC-67.

[b] Technical Aide, Section 17.1-17.2, NDRC.

The oscillograph is to be used to record, simultaneously, six phenomena of a very irregular or nonrecurring type. Accurate measurements are to be made of both the time of occurrence and the magnitude of the phenomena under investigation. The duration of the phenomena may be as long as 1½ seconds. During this time, the sign or direction of the quantity being measured may remain unchanged for periods as long as ¼ second, and even then may be predominantly in one direction. The records may have frequency components of small magnitude as high as 8,000 to 10,000 c, while those components of frequency as high as 5,000 c may be comparable in magnitude to the slower phenomena.

Although the machine will be used as a laboratory research instrument for a large variety of recording operations where facility of control is important, it will at times be required to produce a large quantity of records. It should, therefore, be very reliable in operation and have a simplicity of control that will require a minimum of attention. Covers of simple design are to be placed over all the mechanism with the exception of those controls or indicators which are used during the routine operation of the machine. The latter are to be arranged for convenient manipulation and are to be grouped for easy explanation to new operators.

The oscillograph shall include a paper-transporting mechanism, six recording channels with driver amplifiers, and apparatus for producing timing and base lines on the records. The paper drive shall include the motor and a speed-change mechanism. The six recording channels shall be provided with all associated optical equipment, shutters, the recording lamp or lamps, and the lamp-control apparatus. Six separate driver amplifiers for the recording galvanometers shall be installed. A timing element, separate from the six recording channels, shall be provided, but the frequency-controlled power source for the timing device will not be required. The only external power required, other than the source for the timing lines, shall be supplied by a single-phase a-c power line rated at 105 to 125 v, 60 c ± 0.5 per cent. The entire assembly shall be supported from the floor on rubber-tired casters. The controls shall be at a convenient operating height. The length of the assembly will not be restricted, but the width shall not exceed 26 in.

For the paper drive, a rotating drum-type paper holder for a record length of 65 in. and a width of 6 in. shall be used. A suitable cover shall be provided so that the machine can be operated in daylight, except during loading or unloading. The speed adjustment shall be in two ranges 10 to 50 and 50 to 250 in. per second. Both ranges are to be variable continuously or by at least eight convenient steps. Change in speed range may be made by changing pulleys or gears, if necessary. The paper drive, the motor, and the speed-adjustment mechanism shall be completely enclosed, and the speed control for the high-speed range shall be conveniently located. An indicator, giving the paper speed in inches per second to within 8 per cent shall operate automatically. At any speed setting, the regulation as indicated by measuring the distance between any ten adjacent timing lines shall be within 1 per cent.

The galvanometers shall be aligned to give ¾ in. between traces, with equal borders on each side. The width of the trace shall be not more than 1½ times the minimum possible width as determined by diffraction at the galvanometer mirror. Base lines shall be located close to the second and fifth traces. They shall be exposed close enough to the recording point along the time axis so that only a negligible error will be caused by any probable movement of the film from side to side during the traverse between the recording point and the place where the base lines are exposed. The optical system used for exposing the base lines shall have a wider aperture than that of the recording galvanometers in order that the base lines can be made finer than the record traces without difficulties due to diffraction. Timing lines shall be at least ¼ in. long, and shall have a width of not more than $\frac{1}{100}$ in. They shall be recorded perpendicular to the time axis by means of a galvanometer with its axis of rotation parallel to that of the recording drum. The usable timing lines shall have a spacing of 2 or 10 milliseconds, depending on whether the galvanometer is modulated with a

500-c or a 100-c source. Controls shall be provided for adjusting the amplitude of modulation and the intensity of the recording light for optimum conditions in accordance with the paper speed. An adjustment shall be available for positioning the timing lines anywhere between one edge and the center of the film. The accuracy of the timing lines shall be one part in 5,000 when the driving frequency is accurate to one part in 100,000.

The recording galvanometers shall be mounted 42 in. from the recording position on the paper drum. The drum and galvanometers shall be held in alignment by means of a metal bed which will allow this spacing to be changed to any value up to 46 in. without modifying the external cover over the optical system. The top of the bed shall be from 5½ in. to 6 in. below the optical path between the galvanometer mirrors and the recording point. The galvanometers shall be mounted, not more than ⅞ in. center to center, in adjustable holders that will accommodate either the Model OS3B or OS2B. The cylindrical lens near the paper shall be in a focusing mount supported without obstructing the space immediately below the lens. In order to increase the exposure, the aperture ratio of the cylindrical lens shall be made as large as possible without materially affecting definition. The recording lamp or lamps shall have a line filament and the optical distance from the filament to each of the galvanometer mirrors shall be approximately equal. The alignment of the lamps and any reflecting surface in the optical system shall be adjustable. The recording-lamp current shall be adjustable for exposure control.

Rochelle-salt crystal galvanometers, Model OS3B or equal, shall be used. The overall frequency response (amplifier input to oscillograph trace) to sine waves shall not depart from a straight line by more than ± 2 per cent from 2 to 5,000 c, by more than $+2$ or -10 per cent from 5,000 to 8,000 c, by more than $+4$ per cent above 8,000 c. When a symmetrical square wave with a frequency of 2 c is applied to the input terminals of the recording amplifiers, the wave traced on the oscillograph paper shall not depart from a true square wave by more than 4 per cent in amplitude at any point along the cycle.

The galvanometers shall have a temperature-compensating condenser in the coupling circuit. The amplifier shall be capable of supplying 1,000 v peak to peak to the condenser and galvanometer combination when a signal of not more than 0.2 v peak to peak is applied to the input terminals. In comparison to the voltage gain at 100 v peak to peak output, the gain at 500 v peak to peak output shall be not more than 3 per cent lower and the gain at 1,000 v peak to peak output shall be not more than 10 per cent lower. After a 30-minute warming-up period, the gain vs output voltage calibration shall remain constant within ± 2 per cent over a period of three hours, for line fluctuations of 105 to 125 v and for a line frequency of 60 $\pm$¼ c. These calibrations shall be made with the output impedance in proper adjustment for attaining the specified frequency response and with an input impedance of 5 megohms or more.

The amplifiers shall have at least one inverse-feedback circuit which feeds from the output of the amplifier back to a single-sided stage. The factor $\mu\beta$ for this feedback circuit shall be at least 10.

The overall noise, hum, vibration, or other short-period disturbances shall not cause the trace of any galvanometer to depart from a straight line, parallel to the base lines, by more than ± 1 per cent of the maximum deflection obtained when the output of the amplifier is 1,000 v peak to peak. The test record, in this case, shall be taken at a paper speed of 250 in. per second with the amplifiers turned on and the input terminals short-circuited. After a 30-minute warming-up period and under the following conditions, the trace of any one galvanometer shall not depart from a straight line parallel to the base line by more than ± 3 per cent of the maximum deflection as obtained when the output of the amplifier is 1,000 v peak to peak: (1) the input terminals of the channel under test shall be open-circuited; (2) the test record shall be run at a paper speed of 10 in. per second; (3) full modulation of any or all of the remaining galvanometers shall be allowed; (4) any necessary operation of the controls

during or before recording shall be allowed.

Drawer or cabinet space shall be provided for the storage of extra parts, fuses, cables, etc. The following parts and supplies shall be included with the oscillograph: 4 extra galvanometers, Model OS3B; 10 fuses of each type used; a 30-ft power cord, detachable or on reel; 20 extra lamps of each type burned at photoflood intensity; 10 extra recording lamps, any type; and all special tools required for operation or adjustment of the machine. All controls, lamp switches, shutter-operating mechanisms, etc., that must be manipulated immediately before or after exposure, shall be capable of control from external switches. A cam-operated switch (110-v, 5-amp rating or more) shall make and break a circuit without chatter at each revolution of the recording drum. The point of operation of this switch shall be adjustable to any position around the drum and the position shall be indicated to 1 degree by a graduated circle. Near the amplifier panels, two blank panel spaces for standard 8¾x19-in. panels shall be provided.

Summary of Development

A drum-type recording oscillograph utilizing six direct-coupled amplifiers which drive an equal number of Brush-type OS3B crystal galvanometers through direct-coupled amplifiers having a frequency range from 0 to 8,000 c, was developed and constructed. The instrument was built in a walnut cabinet, 73x36x26 in. mounted on casters for use within the laboratory.

The amplifiers as originally designed and constructed had sufficient gain to give 1-in. peak to peak galvanometer deflection for 30-mv rms input. As shown in Figure 1, six amplifiers, utilizing standard rack and panel construction, are provided on either side of the main cabinet, plus a seventh spare amplifier and two power-supply chassis in the center portion of the cabinet. The complete assembly is controlled from a sloping control panel. The rear portion of the cabinet contains the optical system, the recording drum, the variable-speed drive motor and controls, and the thermostatic galvanometer chamber.

Records are made on strips of sensitized paper on film 6 in. wide at chart speeds between 10 in. and 250 in. per second. Timing lines, spaced 1/100 second apart, are included on the chart, and a stroboscopic system affording timing lines of any frequency up to several thousand cycles per second is provided to facilitate analysis of the galvanometer traces for amplitude and frequency.

Six high-impedance input channels are provided for the introduction of signals from piezoelectric devices or other similar circuits utilized in the measurements for which the instrument was designed.

4.2.3 Description and Technical Information

The various available galvanometers were investigated to determine which could suffice for the frequency response and linearity requirements. The Brush-type OS3B crystal gal-

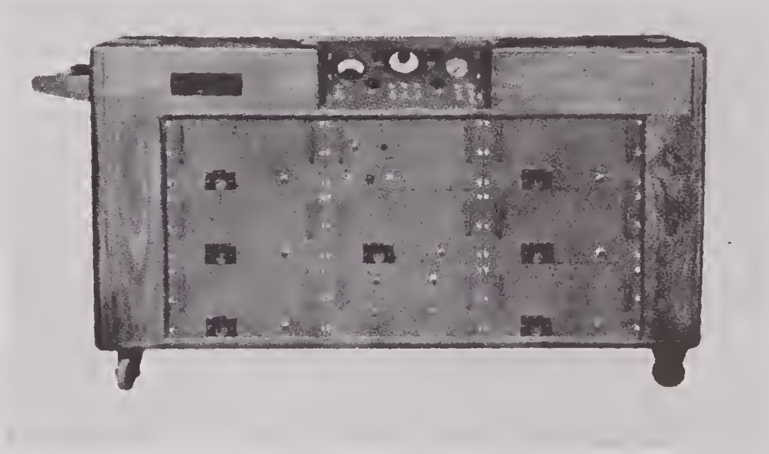

FIGURE 1. Hathaway type S11-A 6-element oscillograph.

vanometer was finally decided upon as satisfactory. However, it required accurate temperature control of the crystal chamber to prevent variations in both frequency and amplitude response. This particular galvanometer was undesirable because it has a very high resonant peak at a frequency of 11,000 c, just outside the band of frequencies requested in the specifications. Furthermore, it is extremely sensitive to voltage overload which would damage the crystal. Thus, in the amplifiers and associated recording equipment, it was necessary to incorporate appropriate compensation and protective circuits, to prevent the resonant peak from influencing the frequency-response characteristics (including transient response) and to preclude damage to the crystal element regardless of the input voltage to the recording unit.

It became necessary to select OS3B galvanometers from a number of units obtained from the Brush Development Company, in order to obtain six sufficiently "identical" in characteristics to make possible the use of a semi-standard amplifier for each channel. Some variation was provided in the amplifier circuits to take care of a few of the variations remaining in these selected units.

The amplifier requirements originally contemplated made it appear possible to use either a d-c amplifier or a very low-frequency response a-c amplifier. Since a-c amplifiers with good low-frequency response usually have long time constants, they tend to exhibit blocking characteristics under overload conditions. This makes it difficult in the presence of momentary overloads to produce records wherein anything save the overload phenomena is faithfully recorded. Accordingly, it was decided to use a modified form of a d-c amplifier originally described in technical literature in 1941.[11] Some of the modifications included the addition of an output stage comprised of a pair of 12J5 tubes in push-pull to give adequate driving voltage for the galvanometer elements. Fortunately, the gain requirements were not excessive, since an input of 30 mv was required to provide an output of approximately 330 v, resulting in a desired gain of approximately 10,000, or 80 db. Frequency-response characteristics of ± 2 per cent from 1 c to 5,000 c, and not over 4 per cent rise or 10 per cent drop between 5,000 c and 8,000 c, necessitated considerable modification of the amplifier circuits in conjunction with the galvanometers as previously mentioned. Two frequency-compensating networks were added to the amplifier, one of these being a high-frequency filter with rather sharp cutoff characteristics placed in the plate circuits of the output tubes. This circuit prevented the frequencies in the vicinity of 11 kc and above from being applied to the galvanometer, thus avoiding excitation of the galvanometer at its resonant frequency. In view of the variation between galvanometers, it was necessary to make this circuit variable to operate correctly with individual units.

There was also included an inverse-feedback circuit frequency selective in itself to some degree, to allow the mid-frequency range to be adjusted to lie within the specifications.

The high input impedance required of the amplifier circuit made the use of triodes in the input stages somewhat difficult, but in view of the regulated voltages necessary, it was decided to continue the use of triodes with their associated cathode-compensation circuits for drift elimination and to add an input network to maintain the input impedance at a value of 1 megohm or greater, from 0 to 8,000 c. The amplifiers finally incorporated as part of the equipment met the majority of the requirements.

The main optical housing of the oscillograph contained in the rear portion of the case consisted of the six galvanometers, a plano-convex lens of 42-in. focal length mounted as an integral part of each galvanometer, a recording lens to focus the trace on the paper or film, a shutter and a recording lamp, two optical baseline markers, and a timing-line system consisting of a neon lamp or synchronous motor-driven shutter. The neon lamp can be supplied with base frequencies from external timing systems. The synchronous motor-driven shutter provides fine-line traces on the record every 0.01 second and double- and quadruple-width lines every 0.05 and 0.1 second, respectively. In addition to these two timing devices, a bifilar galvanometer with an 18-in. focal length lens was supplied, to be used if desired.

To maintain uniform galvanometer characteristics, the chamber includes a thermostatically controlled switch and heating and cooling system utilizing dry ice and a blower to maintain the temperature at 85 F, regardless of ambient temperature conditions. The switch has two sets of contacts which energize either the heater or the cooling blower to maintain this temperature control.

The actual recording drum and drive system is also located within the back part of the main cabinet. The drive consists of a motor whose speed may be varied by changing controls in the thyratron circuit. Speed control of the system is relatively good over a reasonable range. In this particular system step pulleys are used to avoid too wide a range of motor operation for the range of drum speeds needed, which

must provide a maximum paper or film speed of 250 in. per second. Since the entire oscillograph is mobile, it can be wheeled into a dark room where the drum may be loaded under safe light conditions; or with the addition of a lightproof portable canopy, the drum may be loaded in daylight. Paper is held on the periphery of the drum by jam-nut and take-up knob arrangement.

The basic amplifier and power-supply circuits are shown in Figure 2.

3. Beam-triggering circuits to provide for turning three cathode-ray beams on and off at the beginning and end of a record.

4. Time-marking and trigger circuits for placing timing marks on drum-mounted film.

5. Power supplies for three cathode-ray tubes to furnish the following voltages:

a. An accelerating voltage adjustable from 4,000 to 15,000 v negative with respect to ground.

b. A positive voltage for use with intensifier-

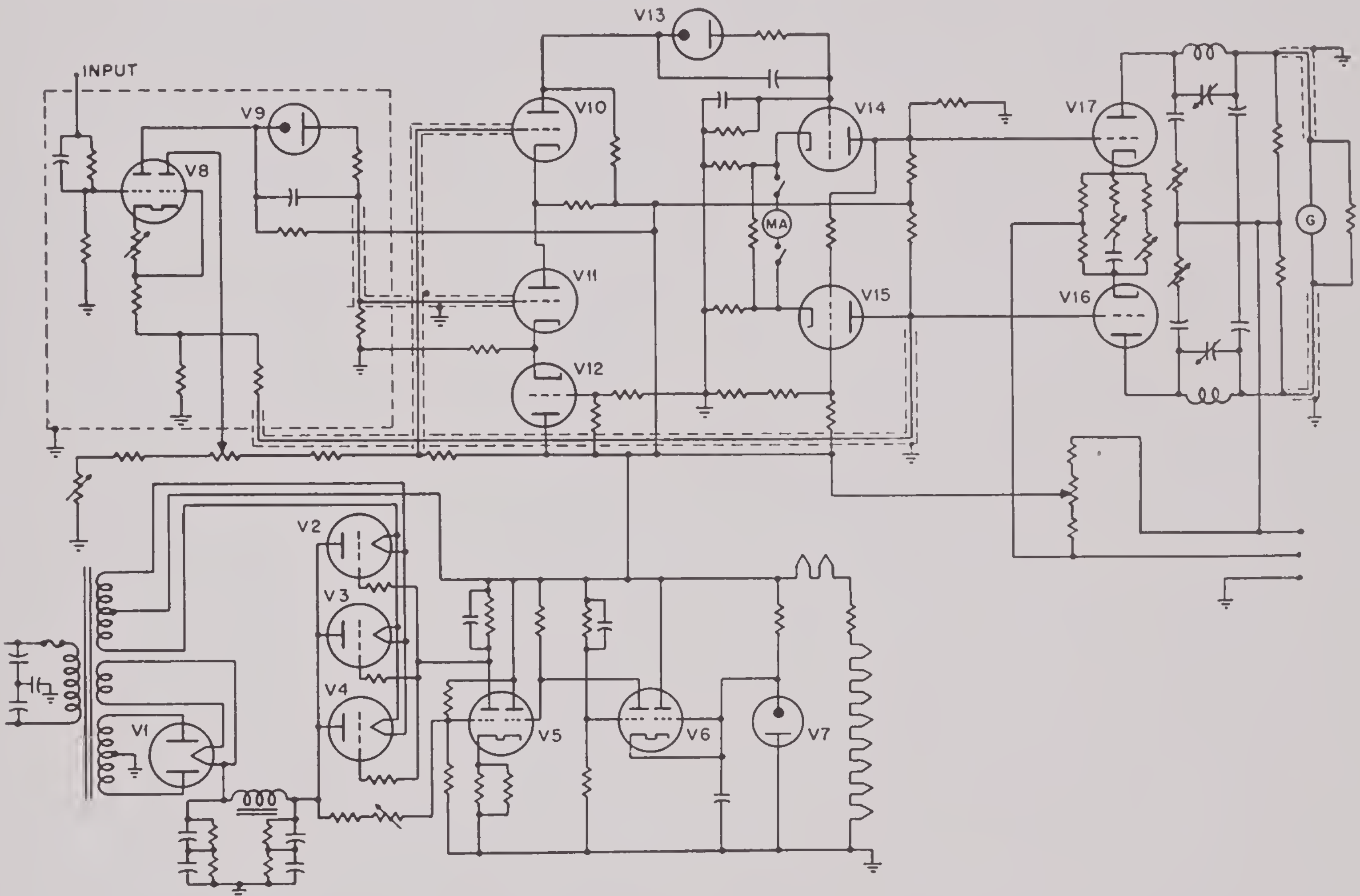

FIGURE 2. Basic amplifier and power-supply circuits for multi-element oscillograph.

4.3 CATHODE-RAY OSCILLOGRAPH (OD-102)[4-7]

4.3.1 Military Requirements

The circuit components required for the high-speed cathode-ray drum-camera oscillograph are the following:

1. Three d-c and three a-c amplifier units with power supplies.

2. Beam-deflecting circuits for controlling and shifting beams of three cathode-ray tubes in order to obtain a long record on a revolving drum.

type cathode-ray tubes, voltage to be variable from 4,000 to 15,000 v.

c. Filament supplies having center-tapped transformers with voltage selecting or adjusting device to accommodate the different filament voltages used in cathode-ray tubes. Three separate transformers and control devices are required.

6. Three amplifiers for modulating the cathode-ray beams with either positive or negative impulses to place timing marks on cathode-ray beams.

7. Three sweep circuits and amplifiers.

The performance requirements and general description of the apparatus were specified by the Aberdeen Proving Ground, as follows.

The drum camera shall consist of a drum, 7 in. wide, mounted on a vertical shaft and enclosed in a light-tight housing which can be sealed air tight and provision made for exhausting the air pressure to a few millimeters of mercury. An arrangement to reduce the air pressure shall be incorporated in order to decrease windage resistance and film flutter. At three positions, separated by 60 degrees, shall be placed high-speed lenses which are corrected to compensate for the curvature of the screen of the cathode-ray tube. At a fourth position provision shall be made for permanently mounting an optical system and apparatus for placing timing marks on the film which is mounted on the drum. The three oscillograph lenses shall be of special design and have air-tight seals at the end next to the camera. Sylphon bellows shall be used to provide for sealing the lenses to the air-tight drum and at the same time allow for focusing the lenses. The mounts for the lenses are to be brackets which are an integral part of the camera housing and table. Rack-and-pinion type focusing mechanisms shall be mounted on the bracket and carry the lenses. The drum shall be driven by a 10-hp d-c motor whose speed is controlled by a Ward Leonard motor-generator type of speed control. Provision is made for loading a strip of film or paper onto the drum through a door which is then made air tight by means of double gasket seals.

Three rubber-tired dollies are to be provided for mounting the cathode-ray tubes, amplifiers, and power supplies. Detachable coupling links provide for lifting two end wheels of the dolly clear of the floor and rigidly anchoring the dolly to the camera table. The dollies are to be constructed in the form of tables and have provision for mounting standard radio-type panels on the sides and back. The cathode-ray tube holder is to be mounted on the table top. At the back of the table top a panel rack is to be supplied to provide for mounting the deflection amplifier immediately over the socket end of the cathode-ray tube. Short direct leads to the deflection plates will thus be possible. Each dolly and its associated equipment will constitute a complete and independent cathode-ray oscilloscope and should be provided with deflection amplifiers, power supplies, sweep circuit, cathode-ray power supplies and control circuits, beam-modulating circuit, single-trace sweep, synchronizing circuits, circuits for triggering the beam on and off, and means for coupling to the amplifiers and disconnecting the amplifier outputs from the oscillograph tube when it is desired to use the amplifier for other purposes.

Since types of cathode-ray tubes change rapidly, provision shall be made for using different types. Only tubes having accelerating-voltage ratings in excess of 5,000 v will be utilized. The rectifier or rectifiers supplying the accelerating voltage will be grounded at the positive end. The accelerating voltage shall be manually and continuously adjustable from 4,000 to 15,000 v. The focusing voltage and accelerating voltage shall be separately variable, but a single control shall permit adjustment from 4,000 to 15,000 v without changing the ratio or relative value of the two voltages. This will provide for focusing the tube at low voltage and then increasing the voltage until the desired writing speed is attained without the necessity of focusing at the high voltage. Controls shall be provided for beam intensity, screen-grid or first-accelerating voltage, focusing voltage, second-anode or accelerating voltage, beam "on-off," horizontal and vertical positioning, fine and coarse adjustment of sweep frequency, synchronizing, z axis, sweep amplitude, test signal, vertical and horizontal amplifier input attenuators, single sweep, trigger beam "on and off" with variable time delay and variable time on. In addition to the accelerating voltage mentioned above (4,000 to 15,000 v, positive grounded), a voltage positive with respect to ground shall be provided for use with tubes having intensifiers, or acceleration of the beam after deflection. This voltage shall be variable from +4,000 to +15,000 v.

Two vertical amplifiers should be provided for each dolly. These amplifiers should be essentially wide-band alternating current or direct-current and have a maximum gain of

60,000 to 100,000 times. The amplifiers should have sufficient output-signal capacity to produce a 5-in. pattern with less than 5 per cent amplitude distortion when 5,000-v accelerating potential between cathode and anode No. 2, and an intensifying voltage of approximately 15,000 v between anode No. 2 and the intensifier electrode are used on the cathode-ray tube. The frequency response should be essentially flat from zero to 1 mc. This should be accomplished by two amplifiers, a d-c and an a-c coupled type. The d-c unit should be flat to 100 to 200 kc. An a-c coupled amplifier having a flat frequency response from approximately 5 c to 4 or 5 mc should be supplied to provide for the high-frequency response. The above signal-amplitude and frequency-response requirements imply that the amplifiers should be capable of producing a still larger signal voltage but with more distortion and that they will amplify, with less gain, frequencies above those specified. Attenuators should be provided with step adjustments to permit selection of a small part of the input signal. The input impedance of the amplifiers should be adjustable, or separate impedance pads should be provided to permit operation in approximately 1,000-ohm, 0.1-, 1-, and 10-megohm ranges. The amplifier would not be expected to meet the high-frequency requirements stated above when the highest impedance input circuit is used.

The horizontal amplifier should have approximately the same characteristics as the vertical, except that the gain need not be more than 2,000 times. Input and output connections should be provided to permit the use of the amplifier with external sweep voltage or for other applications. Switching arrangements should provide for selecting the output of the sweep generator.

All power supplies should operate from a 60-c, 115-v, single-phase line. The power supply for the vertical amplifier consists of at least two separate units. A supply having extremely good voltage regulation by vacuum tube and low effective impedance should be used for the low-voltage stages. A separate high-voltage supply designed to deliver 1,500 to 1,800 v should be used for the plate supply of the power tubes which drive the deflecting plates. Decoupling or padding circuits should be used sufficiently often that regeneration will not occur due to the power-supply impedance. A similar power supply should likewise be used for the horizontal amplifiers.

The sweep-signal generator should produce the conventional type of sawtooth wave form. The voltage-time relations should be as nearly linear as it is practical to attain. The usual controls should be provided, i.e., fine and coarse frequency control, amplitude, synchronization to internal, external, and line frequency. The sweep frequency should be variable from a few cycles to 100,000 c.

The z-axis amplifier should be of the conventional type except that its coupling circuits should be designed to have sufficient voltage insulation to withstand the accelerating voltage. It should be capable of intensifying or suppressing the beam.

No provision has been made for shifting the large drum along its axis, due to the difficulties involved in such an operation. Since the record trace must not move over the same portion of the film for more than one revolution of the drum, it is necessary to provide a circuit for shifting the base line or zero-signal-level line as the record is made. This may be done in one of two ways. A steadily changing voltage may be applied to the deflecting plates or a step voltage could be applied instead. If a voltage having a constant rate of change can be obtained, it would be preferred, since it would produce a spiral on the drum and result in a continuous record. It is further desirable that the rate of change of the voltage be variable in order to control the spacing between the successive traces on the drum for a given drum speed. This would provide for adjusting the length of record or the length of time that is recorded, thus adjusting the time scale to correspond to the phenomenon being investigated.

Since it is difficult to adjust by manual or external automatic means the time delay between the opening of the camera and the occurrence of the signal to be recorded, it is necessary to build into the equipment a circuit for turning the beam on and off. This circuit should have the time on adjustable from 0.01 to 1 second. It should act either through the beam-intensity

control or through one of the amplifiers to deflect the beam off the field of the cathode-ray tube screens when the camera is in the standby position.

A time-delay circuit should be provided to control the interval between the turning on of the beams and the occurrence of the phenomenon to be recorded. It should be possible by automatic means to turn on the beam either before or after a signal is made available for control of the phenomenon under test. For example, if it is desired to investigate a voltage transient which occurs almost instantly after the trigger signal becomes available, the camera should be turned on before the signal is applied to the circuit under investigation. If, on the other hand, it is desired to measure the velocity of a projectile as it passes through two screens placed 100 ft in front of the gun, and the gun is to be fired by a solenoid-operated trigger, the camera should be turned on after approximately the time required for the trigger motor to fire the gun plus the hang-fire and travel time to a position near the first coil. A time range of ± 0.1 second, adjustable in approximately 0.001-second intervals, should be adequate.

A circuit for placing time marks on the film at a rate of 1,000 or 10,000 per second is required. Since the timing marks should not overlap on successive revolutions of the drum, it appears that a cathode-ray tube with associated circuits and optical system should be used. Frequencies of 1,000 or 10,000 c should be available from a quartz-controlled frequency standard. It is desirable to have the marks in the form of short narrow vertical lines or well-defined dots. Electric means can be used to convert the wave form of the time signal into either dots or lines. By intensifying the beam and deflecting it simultaneously, short lines may be obtained. The same spiraling voltage that is applied to the signal-amplifier channels may be used to spiral the timing lines. The application of the timing lines should be synchronized with the on-off action of the trigger circuit.

Standard rack and panel with sub-base construction should be used wherever possible. Unit type of mounting should be used in order to provide for flexibility in choosing the type of functions desired and for ease in servicing and replacement.

4.3.2 Summary of Development

Three complete recording oscillographs, including a-c and d-c amplifiers, regulated power supplies, input attenuators and sweep circuits, were constructed on dollies (designed and built by another contractor) as the major units of the cathode-ray drum-camera oscillograph. Pictures of these dollies are shown in Figures 3 and 4. These three signal units in combination with a fourth timing unit, mounted in a separate rack, comprise the complete oscillograph

FIGURE 3. Oscillograph operating panel.

FIGURE 4. Front view of oscillograph.

assembly utilized in conjunction with a drum camera constructed for the War Department under a different contract. The timing unit supplies various timing and control pulses for the three signal channels to allow the introduction of appropriate timing pips and spiraling voltages for vertical sweep, etc. The timing-unit cabinet rack is shown in Figure 5. All of the various circuits and units are coordinated by a master-control panel which serves to control all beams simultaneously to allow appropriate interrelation between the beams when recorded on the high-speed drum camera. In actual operation, the three signal-channel oscillograph tubes and the timing-signal tube are grouped at 60-degree intervals around the drum, the tube faces being imaged on the recording drum by lenses mounted as an integral part of it. The dollies are thus backed up in position such that the tubes face the recording drum and the separate control panels face outward, while the master-control panel is placed at any convenient location near the recording drum to allow control of both the photographic and electronic operations. The cathode-ray tubes used are 9 in. in diameter, and utilize a short persistence screen (P-5) with a total accelerating voltage of 9,000 to give adequate writing speed for high-frequency-response recording.

Two amplifiers are available for use, one at a time, with any signal channel. When the first of these is used, an overall gain of 3,500 and a frequency response of 5 c to 1 mc are realized. For the second, the frequency response is from direct current to slightly less than 1 mc, with a maximum gain of 5,300.

For horizontal deflection, there is the usual sawtooth time-axis generator having a frequency range from 8 to 120,000 c, accomplished by the use of high-vacuum tubes.

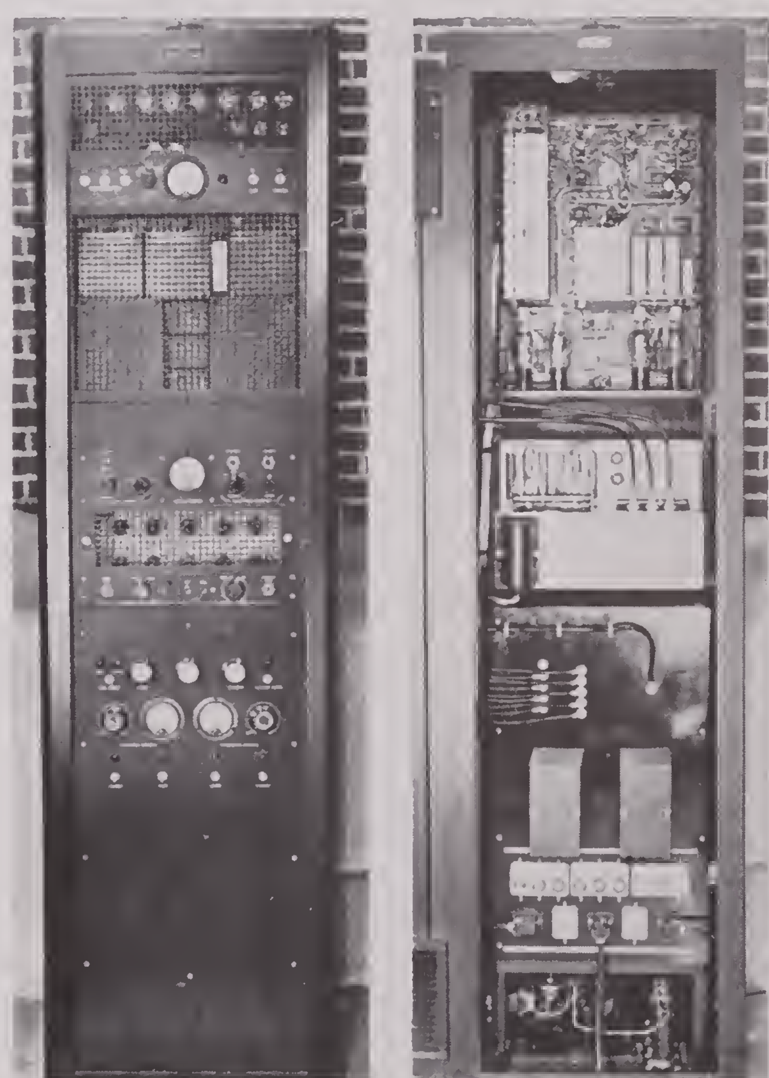

FIGURE 5. Timing-unit cabinet rack.

A single-sweep time axis is also provided to allow analysis of transients under various operating conditions. This single-sweep circuit has a range of 5 microseconds to 1.5 seconds.

The timing-pulse generator, previously mentioned, provides 1½-microsecond timing markers to be inserted into oscillograms at a rate of 10,000 or 1,000 per second, as desired. Finally a z-axis amplifier operates on the cathode-ray beam to intensify the timing pulses or the entire sweep oscillogram, or, if used with reverse polarity, to allow blanking of the return or other undesirable portions of the trace.

pulses to initiate the desired phenomena prior to initiation of single sweep or spiraling sweep for the records to allow appropriate portions to be recorded on the film at the correct times. When the complete apparatus has been adjusted, one single operation automatically begins the complete measurement.

4.3.3 Description and Technical Information

The a-c and d-c vertical amplifiers, the various sweep systems, timing-mark devices, input attenuators and impedance-matching units, phase inverters and signal-mixing circuits, master-control and calibration circuits, plus associated power supplies, cathode-ray tubes, and optical systems, utilized with the equipment, comprise a rather complex interlocking circuit array. It is difficult to simplify description of a system of this type, since oversimplification leads to a misunderstanding of the capabilities of the apparatus, while adequate explanation entails voluminous description and circuit detail.

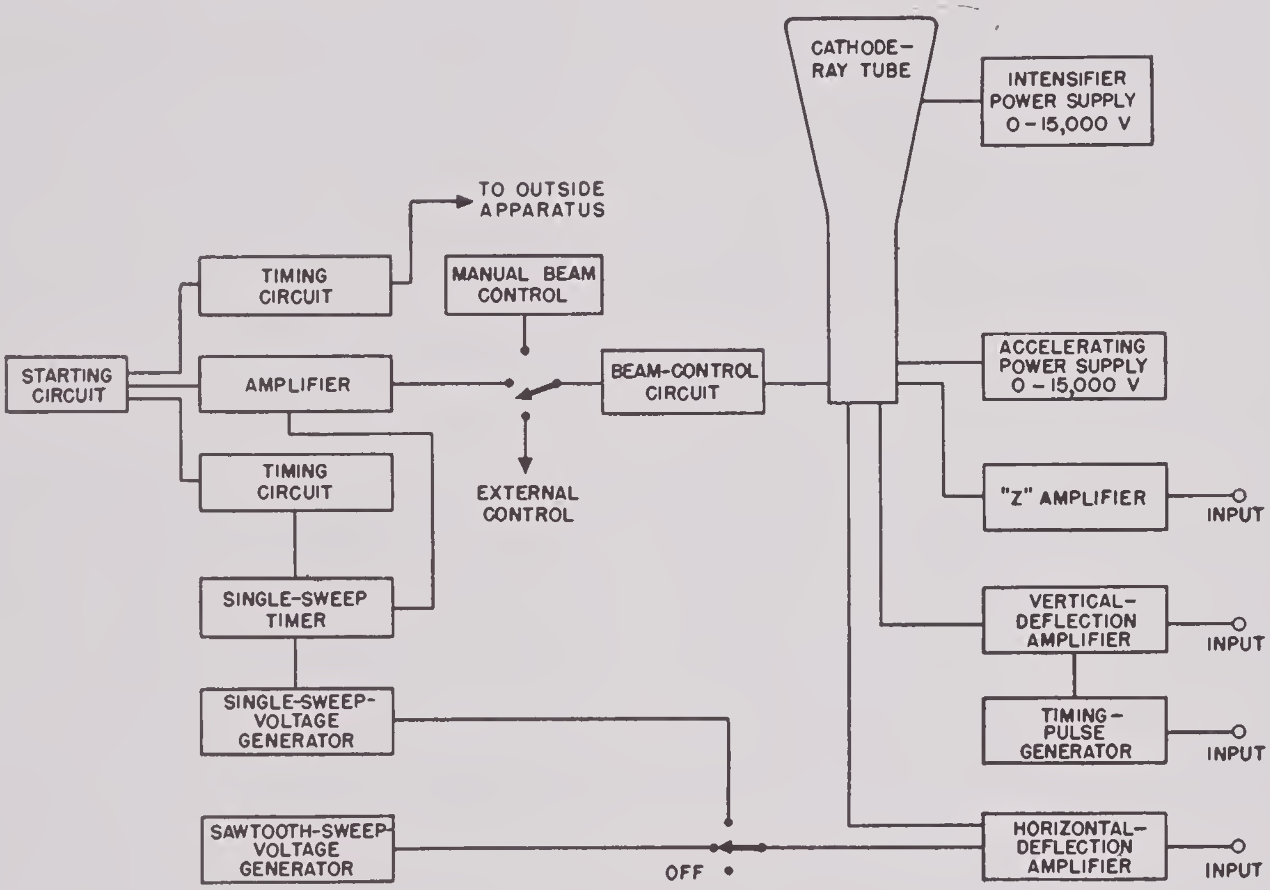

FIGURE 6. Block diagram of oscillograph unit.

The master-control unit, in addition to governing the various sweep voltages which may be applied simultaneously to all three signal channels, also generates a spiraling voltage, i.e., a single vertical-sweep voltage which is applied to all oscillographs equally and simultaneously. Thus, when the oscillograph channels are used with the rotating drum, the drum rotation provides the horizontal time axis, and intelligence to be recorded is superimposed on the spiraling voltage. This allows intelligence signals to be recorded for several revolutions of the drum without overlap.

The master-control unit performs numerous other functions, such as furnishing control

The basic system is shown in Figure 6, a block diagram of the oscillograph, broken down to show one main oscillograph circuit. This particular block diagram is repeated in triplicate for the three signal channels and supplemented by a timing unit noted in Figure 7.

To develop adequate driving voltage to deflect fully the cathode-ray beam of the 9-in. cathode-ray tubes operated with accelerating potentials as high as 10,000 v, output tubes capable

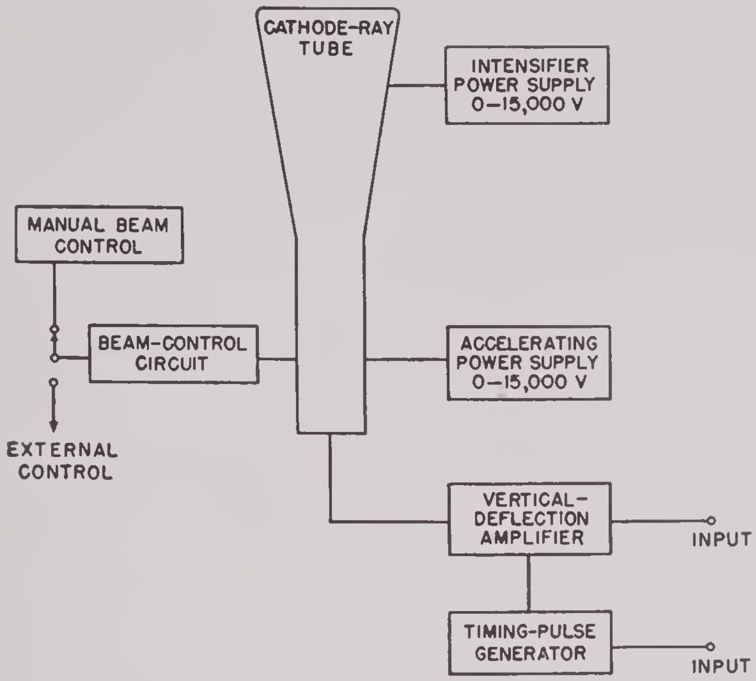

FIGURE 7. Block diagram of oscillograph timing unit.

of producing these voltages are needed. Consideration of this problem led to the employment of Hytron-type HK-257B tubes in the output stages, since they were capable of supplying the necessary deflection voltage and had sufficiently low input capacity to make possible the wide frequency response desired. The overall frequency-response characteristics of the a-c and d-c amplifiers are noted in Figure 8.

A block diagram of the a-c and d-c amplifier circuits and attenuators can be expanded briefly by reference to Figures 9 and 10. These drawings show the a-c and d-c input attenuators, the associated amplifiers and output circuits, and points of introduction for timing pulses, synchronizing signals, sawtooth sweep and spiraling sweep. Study of these circuits reveals that cathode followers are used in numerous instances as impedance transformers and coupling devices having wide-band frequency-response characteristics to d-c as well as a-c signals. The input attenuators are also compensated for linear frequency-response characteristics. In addition to the circuits shown, a separate cathode follower is supplied as an input impedance adaptor, to allow input impedance of the order of 100 megohms to be available for use with certain input devices, such as piezoelectric strain gauges.

The complexity of the construction and development makes it undesirable to go into further detail in this report. The final report[6] and an instruction manual[7] issued under the contract give adequate details on the circuit operation and performance characteristics. To illustrate types of records obtainable with this equipment, a sine wave trace with 10-kc timing pulses introduced from the timing generator unit into the amplifier is shown in Figure 11.

It should be emphasized that the apparatus developed for the NDRC under this particular directive does not comprise a complete recording cathode-ray oscillograph; but, in conjunction with a drum camera and laboratory dollies supplied by the Aberdeen Proving Ground contracts, a complete recording oscillograph was derived.

It should be noted that the separate oscillograph dollies can be removed from connection with the recording drum, described above, and used as entirely independent oscillographs for nonrecording observation of various cir-

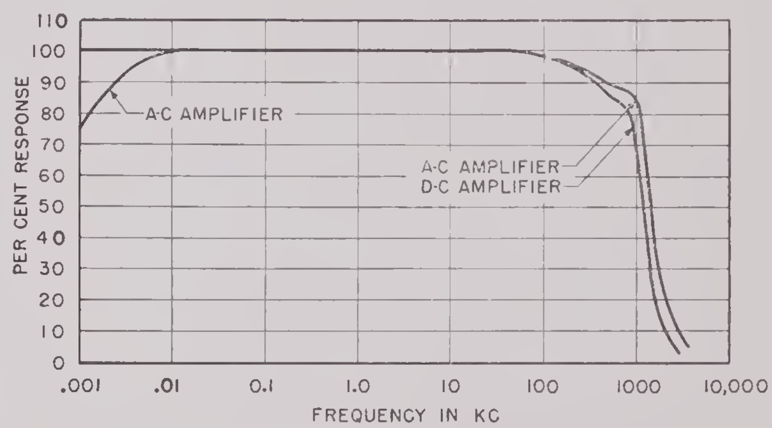

FIGURE 8. Amplifier characteristics.

cuits, since each oscillograph contains its own horizontal and vertical amplifiers and horizontal sweep circuits, attenuators, positioning controls, etc.

4.4 MOBILE MULTI-CHANNEL CATHODE-RAY OSCILLOGRAPH (OD-140)[8,9]

4.4.1 Military Requirements

The final specifications for this development resulted from conference between the contractor and Army and Navy representatives, and from development work and investigations by the contractor. They are as follows:

This oscillograph is intended for measure-

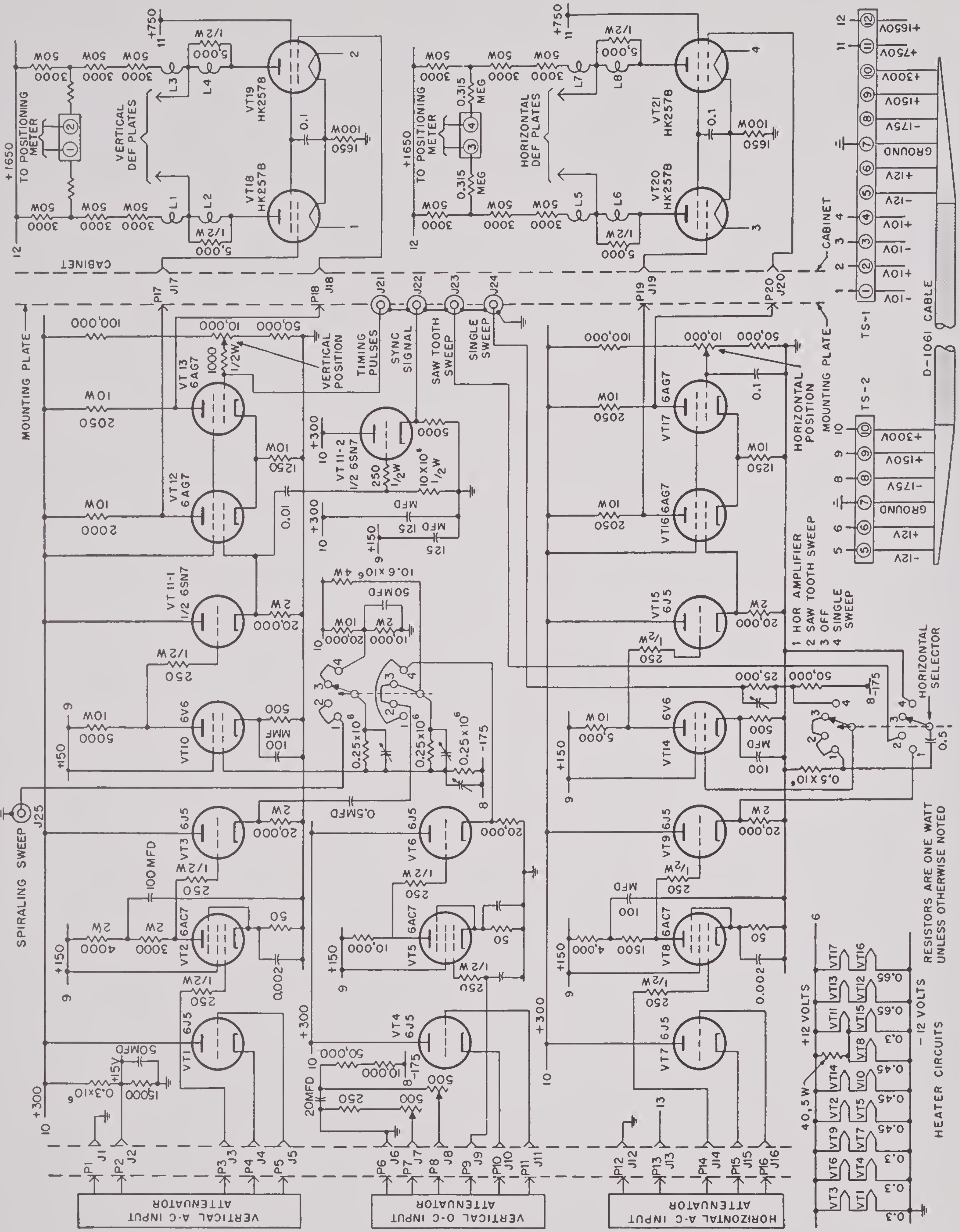

FIGURE 9. Schematic drawing of deflection amplifier.

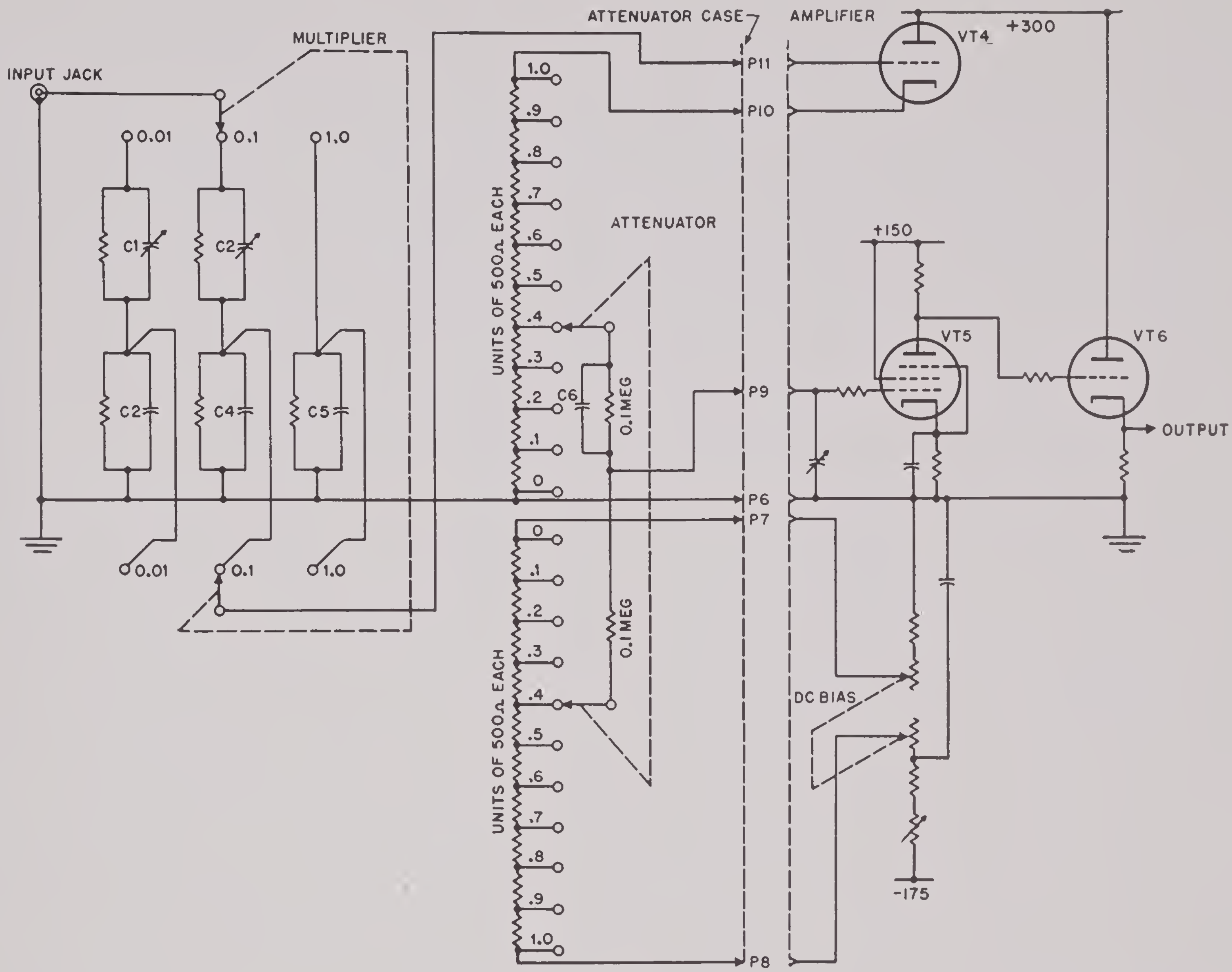

Figure 10. Diagram of d-c input attenuator.

ment of blast pressures, strains, bore pressures, travel time, velocity of the projectile in the barrel, muzzle velocity, and other transient phenomena associated with ordnance engineering. The oscillograph is to have the highest fidelity of response to both high and low frequencies and the greatest electric and mechanical stability consistent with facility of operation and ease of interpretation of the records.

More specifically, the unit is to have four channels, each consisting of input terminals, an amplifier, and a cathode-ray tube. The four cathode-ray tubes are to be mounted on a single panel with their centers at the corners of a 60-degree equilateral parallelogram. The four tubes are to be photographed by a single lens on a strip of moving photographic paper. The horizontal plates of each tube are to be connected to the output of a high-quality amplifier. Timing marks are recorded on the paper simultaneously with recording, to provide time-axis calibration. Voltage calibration circuits are to be incorporated as well as some of the various auxiliary circuits described below, including sequence timers, sweep circuits, square-wave generators, etc.

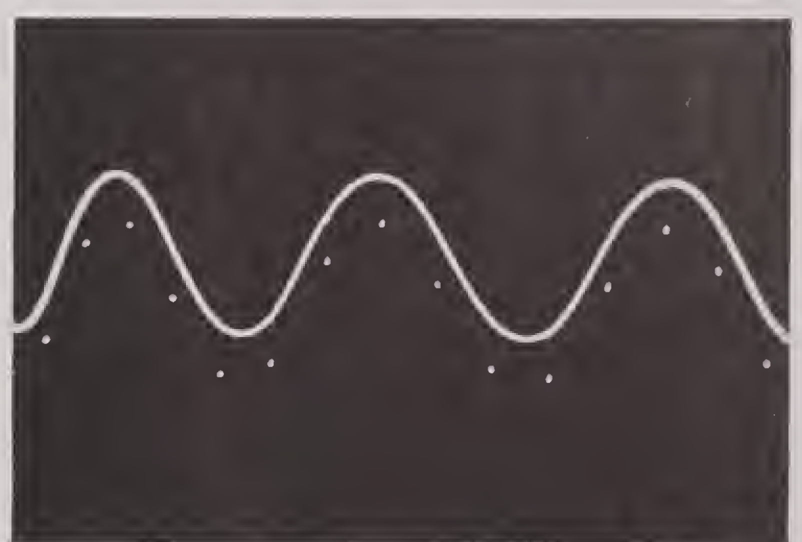

Figure 11. Sine wave trace with 10-kc timing pulses.

The mobile models of this equipment will be built into Army K-72 trailers complete with all auxiliary equipment, including a dark room and workshop. An auxiliary truck will be provided for limited moving of the trailer unit and primarily for carrying the motor-generator equipment. The laboratory models will be semiportable and adapted to semipermanent indoor installation. All units will be complete and self-contained and ready to operate exclusive of the actual measuring elements such as piezoelectric pickups, strain gauges, etc.

Each amplifier should be capable of deflecting the spot over the full useful range of the screen with 0.1 v input. The frequency response should be flat from direct current through 50 kc, and be down not more than 3 per cent at 100 kc. The amplifiers should have a linear phase-shift characteristic over the useful range of frequencies. They should produce a deflection of the spot as nearly linearly proportional to the input as is possible over the useful range of the screen. They should have a high degree of stability to variations of temperature and voltage and be as nonmicrophonic as is reasonably possible. It is very desirable to provide anti-shock mounting and acoustic insulation. The amplifiers should operate from power supplies fed from 110- to 115-v 60-c single-phase mains, or from the gasoline-driven motor-generator sets which are to be supplied. The gain measured with maximum deflection of the spot must be constant as specified over the full frequency range. Both high-impedance (10 megohms) and low-impedance (1,000 ohms) inputs either single-ended or balanced are to be provided. The output stage is to be push-pull. Means should be included to show the operating point of each stage (e.g., a panel galvanometer with a switching arrangement so that each stage can be balanced separately). Gain control is to be provided by the use of an input attenuator calibrated in convenient steps. The spot-centering control may be the last balance control. External connections should be supplied for the input and output of the amplifiers. A suggested method is the provision of a patch-cord panel for connection between the usual signal input source from the pickups or external signal source and the input of the amplifiers. This would provide a convenient method of choosing between balanced or unbalanced, high- or low-impedance inputs of the amplifier and would also allow choice of the amplifier to be used on a particular channel.

Provision should be made for sharp time marks on the paper derived from a crystal standard. If reliable flashing glow tubes are available, a suggested method is to place such tubes on the oscilloscope panel on a horizontal axis between the upper and lower sets of cathode-ray tubes. There would be three tubes on one side and one tube on the opposite side. The film record would thus have a series of single dots along one side and single, double, and triple dots on the opposite one. The single dots would correspond to 1-millisecond intervals, the double dots to 5-millisecond intervals, and the triple dots on one side to either 10- or 100-millisecond intervals. The choice between 10 milliseconds or 100 milliseconds would be made by means of a suitable switch. Regardless of the appearance of the timing marks (lines or dots) it is essential that they be at least as sharp as the recorded traces of the cathode-ray tubes. A crystal standard timing source is preferred such as the Gibbs oscillator or similar type developed by the contractor.

A camera using strip-paper film 70 mm wide is desired. The paper should be delivered from the camera either directly into the dark room or into a tight box which may be carried into the dark room. The Smith type of tank developing is preferred. The mechanical design of the camera should be such that the paper can be accelerated to full speed within 25 milliseconds and that film spoilage or breakage be minimized. Provision should be made for a storage roll of at least 200 ft of paper film. The camera should be completely automatic in operation as long as the film supply lasts and there should be provision for preselecting the paper speed and any length of record from 1 ft to 20 ft. There should be an indicating counter to reveal the amount of footage remaining on the storage roll and an automatic device to cut the film at the right length at the end of a record run. There should be no necessity for rethreading film between records until the storage roll has to be replaced. There should also be provision

for indicating on the film the record number and the time, just before a record is taken. It is preferred that this operation be automatic and take place just before voltage calibration. Either step-wise or continuous control of paper speed would be acceptable. It is desired that this speed be variable from 10 in. per second to at least 250 and preferably to 500. It is suggested that the cathode-ray tubes be photographed at an 8 to 1 reduction. The lens should have a focal length of 6 to 6.5 in. and an aperture of F/2.5, or larger. The image should be sharp over the entire field of view. There should be a control to intensify the beam to photographic brilliance automatically just before the camera is started. The camera itself should be operated by an electromagnetic control so that it can be started by the sequence timer, push button, or other switching means either within the trailer or at some remote point. Means should be provided for properly focusing the camera and for easily checking its focusing at any time.

The use of the 9-in cathode-ray tube, DuMont EX-1829, was decided upon. Originally, a 2514C9 tube was considered, but tests made by the contractor proved that the former had more advantages. While the electric characteristics and screen brightness are the same for both tubes, the DuMont tube has a flat face and is more stable and easier to produce. Provision should be made for adjusting the inclination of the tube for the best compromise between linearity of deflection and focus.

It is desired that voltage calibration in ten steps be recorded on film before each run. It has been suggested that this calibration be applied while the camera is coming up to speed or that the calibration be photographed before the film is accelerated, and possibly simultaneously with photographing the time and identification number. In the latter case the calibrating switch could be either manually operated or motor driven. The final decision must await tests on the present camera, plus further consultation with Aberdeen and Dahlgren Proving Grounds. In any case the switching device must provide positive contact without chatter, and the time constant of the circuits involved should be less than one-tenth the minimum duration of the step.

A device should be provided for voltage, charge or resistance calibration, depending upon whether the equipment is being used for recording circuit transients, piezoelectric gauges, or strain gauges, respectively. The voltage calibration should be against a standard cell. The range of calibration steps should be from 0 to full-scale in ten equal steps. The amount of voltage should therefore be adjustable to accord with the gain setting of the amplifier. For charge calibration there should be provided a decade capacitor so connected that it can be charged from a constant-voltage source and discharged into the ballast capacitance. A mechanical arrangement should be provided so that this operation can be repeated ten times in succession. The calibrating capacitor should remain connected into the ballast capacitance while the test is being recorded. For resistance calibration a rotating contactor similar to that used for voltage calibration could be used. Means should also be provided for photographing a zero-level base line for the duration of the record. This level should correspond to the zero level indicated by the voltage calibration.

The sequence timer is to consist of ten relays operating in sequence with interlock. Each interval should be adjustable from zero to two seconds in ten steps. Neon bulbs should be provided for visual indication and the interlocking device should prevent subsequent functions if any stage fails to operate. There should be provision for easy connection of external operations to the sequence timer. Each stage should have available two double-pole, double-throw sets of contacts.

A muzzle-contact circuit should be provided which will supply a pulse adjustable in amplitude and duration applicable to the input of the amplifier. This circuit should work from either a make or break contact.

A mica capacitor of 10 μf in ten equal steps should be supplied for each channel for use as ballast in piezoelectric measurements. Also, as mentioned under voltage calibration, a General Radio decade capacitor or equivalent consisting of three banks of 0.001, 0.01, and 0.1 μf units should be provided for calibration.

In addition to the circuits mentioned, a square-wave generator for visual check on

amplifier performance will be necessary. There must also be supplied a sweep circuit with necessary amplifiers and means for applying a sweep voltage to each of the tubes. A local oscillator, which will give a sinusoidal voltage from 20 c to 200 kc, is desired.

There should be provided an intercommunication system with two pickups without call-back feature, two 1,000-ft lines on reels, and a public-address system with a 50-w output from a blast-proof directional speaker with directional control within the trailer.

An S-27 or Hallicrafter's SX-28 receiver should be provided. Also, the trailer units should be furnished with an SCR-610 receiver to be supplied by the Ballistics Research Laboratory, Aberdeen.

Voltage should be regulated either on the a-c mains or at the output of all the power supplies, so that calibration of the beam deflections can be relied upon to one-half per cent.

All relay racks should be grounded to the frame of the trailer. The circuits should be wired so that the chassis is not connected in any way to these circuits, but an insulated terminal should be provided on the rear of each chassis for a ground connection for the circuits. Also, there should be a terminal post on the frame of the trailer for a direct ground connection.

Two 10-kw gasoline-driven motor-generator sets should be provided on a separate truck. Both should have the same electrical characteristics so that in the event of failure of one the alternate could be used on the same circuit. The truck of these motor-generator sets should be capable of moving the trailer in a limited manner, but not necessarily capable of towing the trailer over highways. For this reason both push and pull pintles should be provided. The truck should have two 30-gallon gasoline tanks and should be equipped with fire extinguishing equipment. Provision should also be made for operating the trailer unit on a-c mains of 110-v, single-phase, 60 c. The use of voltage-regulating transformers is recommended in this connection. Provision should be made for easy switching between a-c mains and motor-generator sets, and there should be precautions so that it is impossible to switch both power sources on at the same time.

All components should be of first grade. Wire-wound resistors should be used wherever needed. Electrolytic capacitors should be avoided throughout, and step-wise selector switches should be used in place of continuously variable potentiometers. The insulation must be of a type not affected by moisture. All wiring between units should be in metal channels. The insulation should be at least 100 per cent over standard specifications. Transformers should be adequately shielded and insulated throughout.

The trailer should be air conditioned with sufficient capacity to keep the relative humidity below 40 per cent under working conditions. Strip electric heaters are to be incorporated, so that the same blower and duct system can be used to distribute conditioned or heated air. This system should be supplied by the contractor.

Dust covers are to be provided on all circuits where the accumulation of dust would be detrimental to the operation of the unit. This applies especially to relays and similar contacting devices. In this connection, it is suggested that a glass cover be provided for the cathode-ray oscilloscope panel and possibly a metal cover to be used in transit.

A paper drier should be provided of the squirrel-cage or infrared types.

The complete unit is to be housed in a K-72 Army trailer, these units to be supplied by the Ballistics Research Laboratory. The contractor will make all necessary modifications.

The trailer should contain a dark room for developing paper film with all necessary equipment such as safe lights, timing clock, cupboards, Smith developing unit, fluid measures, thermometers, driers, etc. The sink shall be of stainless steel. There should also be included a 100-gallon copper water tank with external connections through the floor for filling and overflow. The tank should be piped to the sink with gravity feed and have a glass water-level gauge. A shop shall be provided with adequate and convenient a-c outlets and a work bench with drawers or cupboards for tools and small parts.

There are to be twelve reels of cable beneath the trailer in weather-proof boxes, so mounted that each reel can be wound conveniently and independently of the others. Each reel should be

provided with a receptacle so that the input jack can be connected after the cable is unreeled. Signal Corps reels DR-5 and DR-4 are suggested. Each cable should be 1,000 ft long. The cables will consist of the following: four coaxial cables; four twisted-pair shielded cables for the inputs; two twisted-pair intercommunication cables; one twisted-pair trigger line; one twisted-pair muzzle-contact line. These cables are to be rubber covered if possible. It is suggested that one of the communication lines be a twisted pair of No. 14 copper wire for alternative use as an a-c power line. There shall also be 200-ft lengths of rubber-covered cable for connection between the motor-generator truck and the trailer unit. It is desirable to have remote starting control for the motor-generator sets in the trailer.

The construction of the whole unit should be as rugged and durable as is consistent with design considerations. All sensitive circuits or mechanical assemblies should be completely anti-shock mounted.

The trailer should be provided with fire extinguishing equipment, first-aid kits, hand tools for electronic work, a 3-in. cathode-ray oscilloscope, an RCA junior volt-ohmyst or equivalent, and a Simpson volt-ohm-meter or equivalent.

4.4.2 Summary of Development

A four-channel cathode-ray oscillograph complete with high-speed strip-paper recording camera, associated sequence-timer circuits, power supplies, sweep circuits, and control circuits, was developed, constructed, and installed in a K-72 four-wheel Army trailer with associated gasoline-driven prime-power sources installed in a K-53 Army tractor truck. The two units comprised a system available for field use for the recording of various ballistics measurements utilizing strain gauges of the piezoelectric and wire-resistance types of input signals. To facilitate field use, the trailers were also equipped with intercommunication systems, high-power public-address systems, and two-way radio communication. Dark rooms, air-conditioning, heating, work shops, and test instruments were also supplied for maintenance of the apparatus and its operation during the usual variations of weather in the vicinity of the Aberdeen or Dahlgren Proving Grounds.

The four intelligence channels of the oscillographs consist of four d-c amplifiers designed by representatives of the Aberdeen Proving Ground and adapted to the operation of 9-in. cathode-ray tubes with a total accelerating potential of 10,000 v. The wiring diagram of the d-c amplifier is shown in Figure 12. The four tubes are mounted on a single panel with their centers at corners of a 60-degree equilateral parallelogram, so that they can be photographed by the single lens of the strip-paper camera. Timing marks are also recorded by this camera simultaneously with the recording of the cathode-ray traces. This is done by use of flasher lamps driven by appropriate oscillator circuits, the lamps being located on the same panel and in the same focal plane as the cathode-ray traces.

There are sweep circuits of the usual sawtooth variety for study of the operation of each tube prior to photographic recording. However, during the recording period, the time axis is provided by the moving paper rather than by an electronic sweep circuit.

A sequence timer is provided for timing of initiation of the field phenomena, starting of the camera, increase in cathode-ray tube illumination, automatic calibration, and so forth. This makes it possible to record the necessary information on a relatively short piece of paper, even at extremely high paper speeds. The general arrangement of the apparatus is shown in Figure 13.

The camera utilizes 70-mm paper, obtainable in 200-ft rolls, and is capable of producing speeds from 10 to 500 in. per second, with a number of steps in speed. The camera operation is almost completely automatic. After the appropriate record length has been selected and the paper cut off within the camera by the operation of proper controls, the motion of the paper past the lens is begun by the sequence timer. Following exposure, the paper is delivered directly to the dark room through a light-tight chute for immediate development. The camera is so designed that cutting off the paper is followed by automatic threading of the paper between the friction-drive rolls, so that no rethreading for the next run is necessary. This

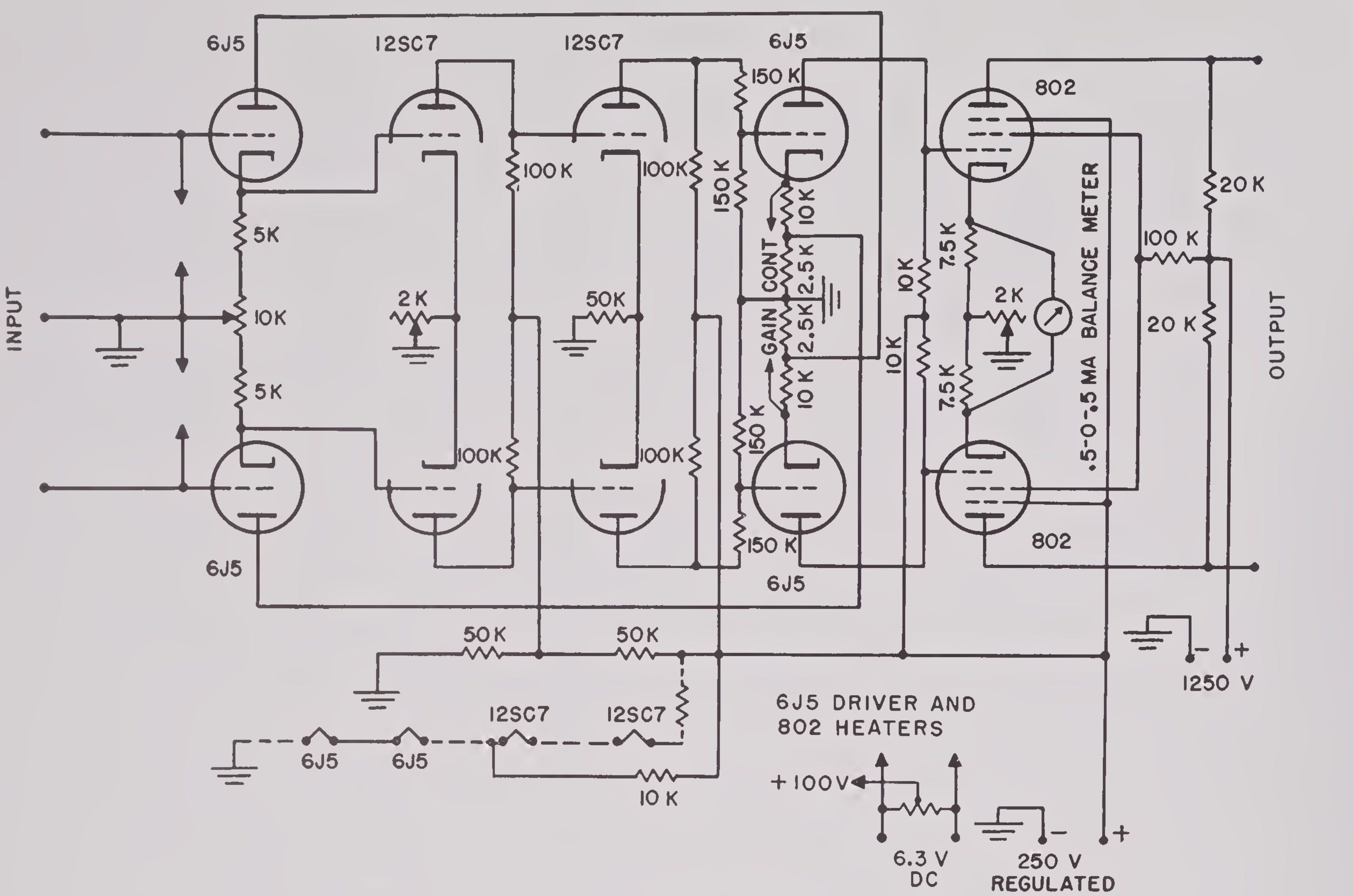

FIGURE 12. Putnam d-c amplifier.

makes a rapid series of runs possible. Interlocking controls are provided to avoid faulty operation of various units. Acceleration of the camera to even maximum recording speed is accomplished in less than a millisecond without damage to the paper.

The trailer and tractor truck are supplied with reels to hold various cables for transmitting intelligence signals to and from the truck for intercommunication and for connection of the two gasoline-driven motor-generator sets to the trailer circuits. Thus, the complete assembly consists of a trailer and truck unit, self-powered, with adequate apparatus to allow the taking of records containing frequency characteristics from 0 to 100 kc.

In addition to the development of this particular unit, which is in process of duplication for use by the Navy at Dahlgren Proving Ground, a similar, less elaborate system, mounted on dollies, was under construction for use within the laboratory only. This latter system contained all the main features described above, except the separate power supply, the trailer, the truck, and the dark room and work shop facilities.

4.4.3 Description and Technical Information

The physical characteristics and requirements of this apparatus are adequately outlined by means of the military requirements and specifications noted above, the drawing of the interior trailer arrangement (Figure 13) and the description in Section 4.4.2. The actual amplifier circuit used to drive the cathode-ray tube is one designed for the Aberdeen Proving Ground, as has been previously stated, and is known as the Putnam amplifier. The basic circuit is given in Figure 12. Certain minor modifications were made to adapt the amplifier to the operation of the 10-kw cathode-ray tubes. The following comments on this amplifier circuit may prove of interest.

The effective input impedance is approximately 100 megohms, since the input tubes are operated at a stable grid potential point, i.e., where the free grid potential is approximately 0 v. No d-c return need be provided in the amplifier circuit, the actual return being effected by leakage paths in cables attached to the amplifier during tests.

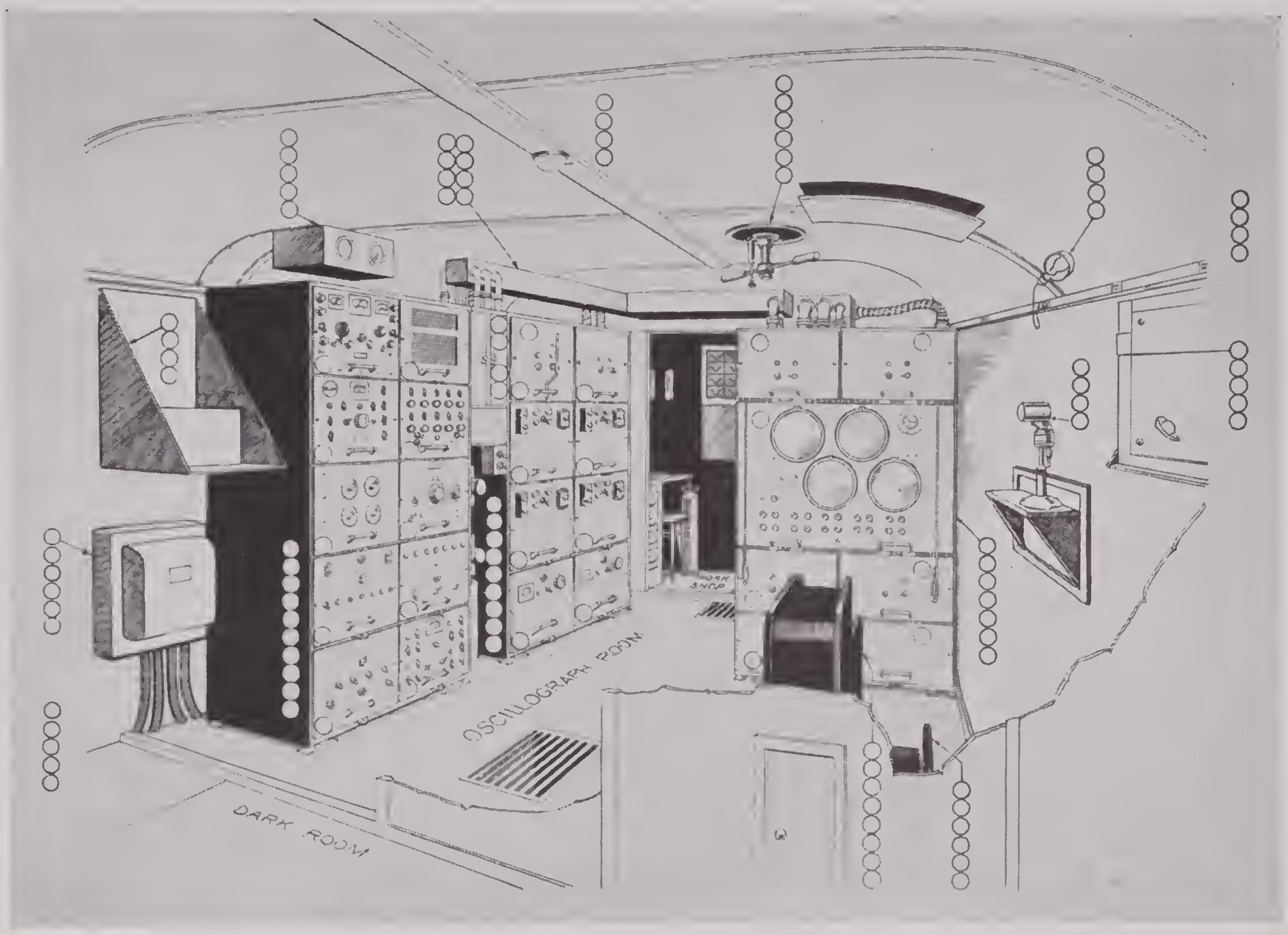

FIGURE 13. Mobile oscillograph interior.

The amplifier can be used either single ended or push pull, merely by shorting out one grid, since the third stage automatically acts as a phase inverter. The response of the amplifier is essentially flat from d-c to 70 kc. It is only down about 20 per cent at 100 kc. The maximum output voltage is approximately 600 v peak to peak. If preaged tubes are used in setting up the amplifier for operation, it is quite stable over long periods of time. The usual method for aging tubes is to apply normal heater-voltage and space-current conditions for 100 hours continuously prior to installation.

The sequence timer consists of ten four-pole double-throw latch-type relays, used in the plate circuits of thyratrons. The controlled contacts are adaptable by means of patch panels to control any of the various items which must be synchronized, such as camera starting, tube-beam intensification, gun or bomb detonation, and calibration. The sequence timer can be set to have a range of timing intervals between the various channels from less than 0.02 second to 2.0 seconds in ten steps. It is based on variable RC time-delay circuits with interlocking control between the various channels.

The pulse circuit, used to place timing marks on the paper, is comprised of a series of flasher tubes photographed in the same plane as the ends of cathode-ray tubes. These tubes are energized by a special arrangement of "flip-flop" circuits and countercircuits used to divide the output of a 100-kc crystal oscillator down to frequencies of 1,000, 500, 100, 50, and 10 c. If desired, calibration is provided automatically at the beginning of each record for charge, resistance, or voltage variations. This is effected by means of a spring-driven rotary switch, the contacts of which are so arranged that ten steps of calibration in addition to zero level for any of the three items noted can be introduced into any or all input circuits at the beginning of each record. The steps extend equally in a positive and negative direction and produce stair-step traces on the record to allow deter-

mination of amplifier gain for accurate measurement.

The camera operation can be understood by brief reference to Figure 14. While this diagram is oversimplified, the operation of the camera might be outlined as follows. Paper is unwound from the storage roll, *S*, and stored

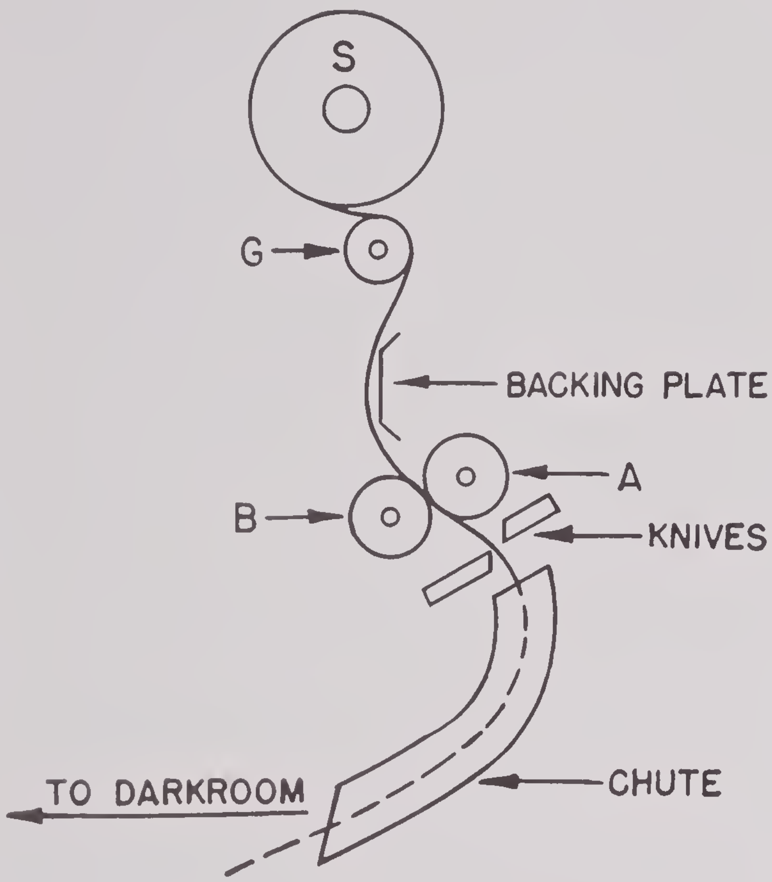

FIGURE 14. Paper-drive mechanism.

in a storage bin (not shown). The paper is precut to length, which makes it unnecessary to bring the storage roll up to speed. When the camera is started (prior to actual starting of the film or paper motion), drive roll *A* is running at a preselected speed. The end of the paper rests between the separated drive rolls *A* and *B*, protruding just slightly beyond the line of contact. To start the film, *B* is pressed against the paper and the action of the rollers then pulls the paper through the camera. At the end of the run, roll *B* springs back, thus stopping the drive while the paper is delivered directly from the camera via a stainless-steel chute into a dark room. The action of *B* is controlled by a powerful solenoid which gives practically instantaneous acceleration, since the inertia of the drive system connected to roller *A* is low and the power of the motor is sufficient to overcome the load imposed by the paper and drive roll *B*. Actually, *B* is geared to drive *A* in such a fashion that it is also rotating prior to contacting of the two rolls. The camera operation has been found to be quite satisfactory.

The complete assembly is supplied with power from two 10-kw generators driven by gasoline engines mounted in a K-53 truck. These generators are automatically regulated by means of the speed control on the gasoline engine. The output is 110 v, 60 c, which makes it possible to operate the complete equipment without the truck when it is in the vicinity of commercial power source.

Various auxiliary circuits are supplied, as specified in the military requirements, to allow the appropriate introduction and interpretation of signals. In addition, test equipment, consisting of a square-wave generator, a sinusoidal oscillator, voltmeters, and analyzers, is available as part of the work room contained at the rear end of the trailer. A radio receiver is provided for checking the timing-pulse-generator frequency against standard frequencies derived from Radio Station WWV. In addition, as previously stated, intercommunication apparatus, high-powered public-address apparatus with a rotary externally mounted speaker, and two-way radio telephone are provided to maintain contact with central laboratory facilities, aircraft in bombing tests, and personnel working in the field outside of the trailer.

4.5 ARMY AIR FORCES INSTRUMENT TRAILER (AC-67)[10]

4.5.1 Military Requirements

The required military characteristics were as follows.

1. The apparatus was to record the time of occurrence for a minimum of seven events.

2. It was to measure and record intervals of time as follows.
   a. from 0 to 1 minute, with an accuracy of 0.001 second;
   b. from 0 to 1 hour, with an accuracy of 0.1 second;
   c. intermediate periods of time if (a) and (b) could not be met.

3. The trailer was to have a source of power for operation of the apparatus.

4. There was to be a radio for communication and signal-transfer purposes with the control station at Eglin Field and also with airplanes in flight. (It was later suggested that a special signaling device operating from bomb or trigger switches through the regular radio equipment should generate the signal to be picked up by the ground station in the instrument trailer. The special signaling device should fit into any airplane, require less than ¾ hour for installation, require no specialized personnel, and operate on both very high and standard frequencies.)

5. There was to be provision for heat for cold-weather operation and for ventilation for hot weather. (The completed trailer has a fan for ventilation purposes.)

6. There was to be provision for control of humidity to a degree sufficient to protect the installed apparatus. (There is no provision for humidity control in the completed trailer.)

7. The trailer was to be of sufficient size to accommodate the installed apparatus and to provide working space for the operating personnel; trailer construction was immaterial provided it had sufficient wheel bearing area to enable it to be hauled over sand roads.

In conferences held after initial study of the problem it was agreed that the contractor should supply and install certain specific equipment: a multi-channel, multi-speed oscillograph; adjustable input channels for signals of varied strength; appropriate amplifiers for use with geophones, hydrophones, and photocells; set of geophones and hydrophones (12 each) (or microphones, should they prove superior to geophones); apparatus for signaling occurrence of an event from plane to trailer; facilities for developing paper; and two 5-in. cathode-ray oscilloscopes. In addition to providing this equipment, the contractor was to undertake experiments to determine the practicality of using light-sensitive cells to determine time of burst for on-the-ground and low-altitude explosions, the cells' pickup to be useful at distances greater than 500 ft. Suitable changes were to be made in the designated equipment in line with the results of these experiments.

The Army Air Forces Proving Ground Command agreed to furnish radio transmitters and receivers; office-type trailer for housing all the equipment; 120 ampere-hour batteries, 24-28 v; 1-kw energizer; and a 28-d-c to 110-a-c 250-w inverter.

4.5.2 Summary of Development

The completed instrument trailer has a 24-element galvanometer and associated recording equipment, which provides for recording a considerably larger number of events than was originally requested. For a desired accuracy of 0.001 second the recording-paper speed must be about 25 cm per second, which, for an interval of 30 to 60 seconds, would give an impossibly long record. However, such accuracy is usually needed only during a small portion of a run; and, if the operator is forewarned, as he ordinarily will be, of the portions requiring such accuracy, the operation can be carried out at variable speeds in such a way as to provide the required accuracy during a run of one minute. With available paper speeds, the longest possible run would be about 3 minutes; however, the recording galvanometer is of such versatility that moderate modification would meet the re-

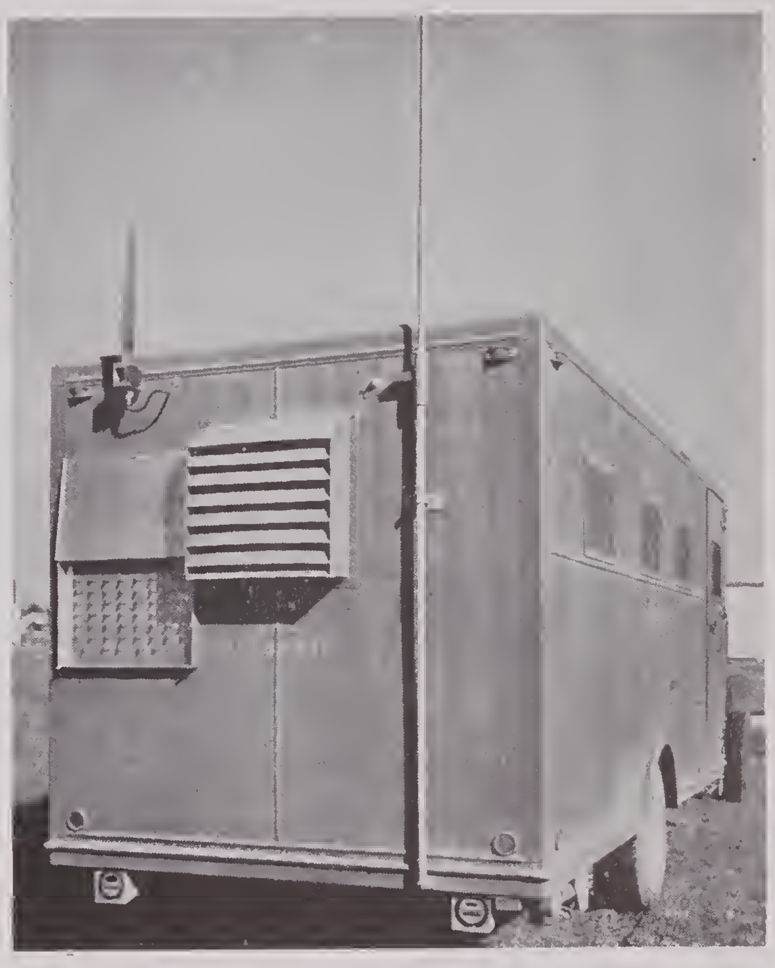

FIGURE 15. Rear view of trailer showing terminal panel and radio antennas.

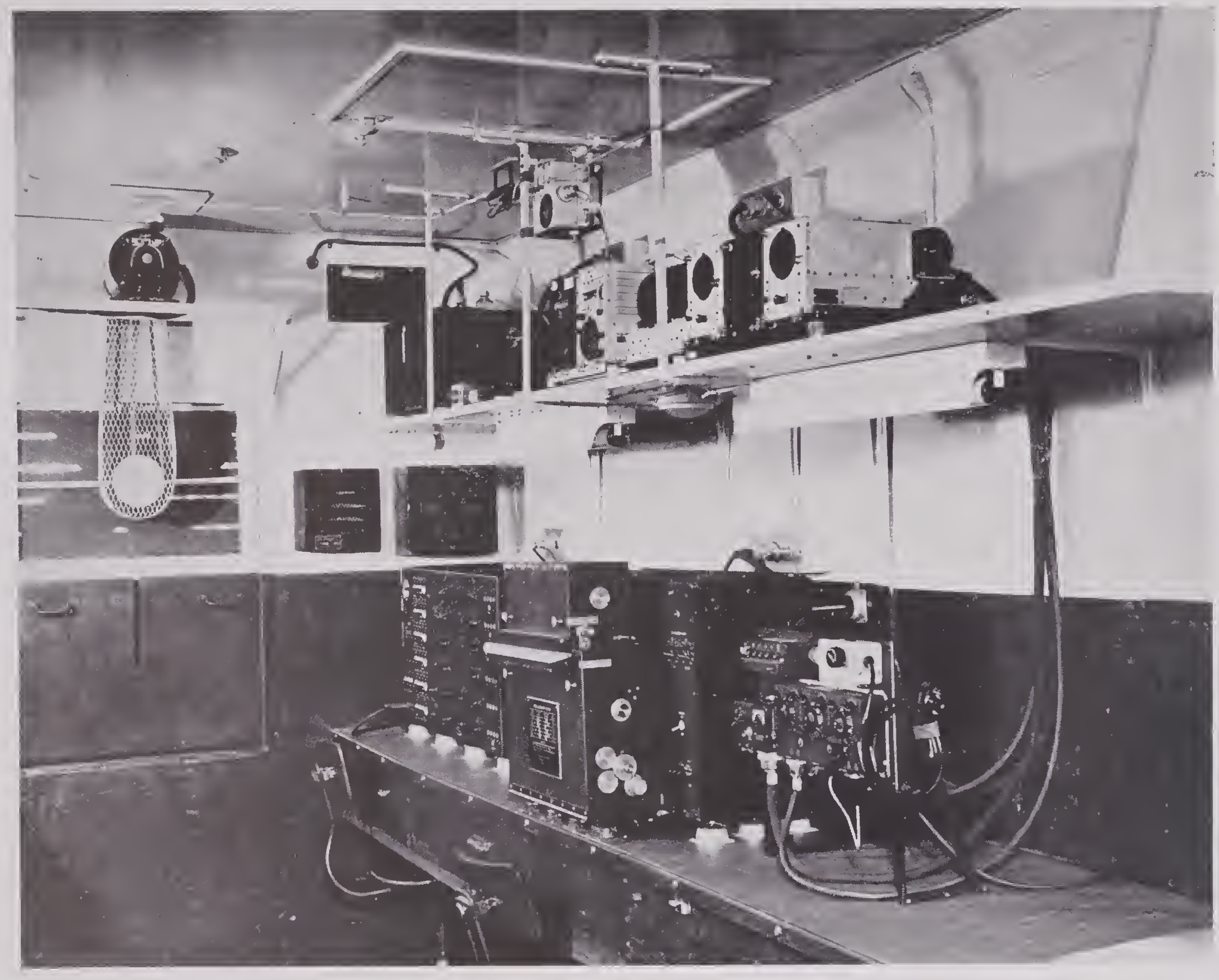

FIGURE 16. Interior view of rear end of trailer showing instrument installation.

quirement for recording from 0 to 1 hour with an accuracy of 0.1 second. In addition, an appropriate and acceptable method for signaling from plane to trailer was developed and the necessary apparatus supplementary to the operation of the trailer was supplied.

4.5.3 Description and Technical Information

Figure 15 is a photograph of the exterior of the trailer with the radio antennas and the input panel mounted on the rear. Figure 16 is an interior view of the rear end of the trailer showing the instrument installation. Storage batteries are provided as the fundamental source of power.

The most important item of equipment is the oscillograph, which consists of a 24-element galvanometer, motor-driven multiple-speed camera, control circuit, power circuit, and timing equipment. The camera has paper speeds of 5, 12.5, 25, 50, 125, and 250 cm per second, and is designed so that at any of these speeds the paper speed is independent of the quantity of paper on the dispensing or receiving roll. Speeds as high as 350 cm per second can be obtained, but above 250 cm per second the speed control is poor. The camera uses 200-ft rolls of paper 10, 20, or 30 cm in width.

The construction of the multi-element moving-coil galvanometer is illustrated diagrammatically in Figure 17. The galvanometer elements are in individual cylinders which can be supported in the steel racks, *C*. An inner pole piece is mounted within the cylinder; an outer pole piece is inserted in the walls of the cylinder and serves to make magnetic contact between the inner pole piece near the coil and the steel rack in which all the elements are

mounted and which is subject to the magnetic fields of the permanent magnets *D* attached to its back. Light from a common source is reflected by prisms onto the mirror of each galvanometer element, and, from the mirrors, passes through an optical system to the recording paper.

The resistance of the galvanometer element is about 20 ohms. Its natural frequency is 110 to 120 c; mechanical shock will cause the coil to vibrate slightly at about 230 c. A direct current of 1 microampere causes a light-spot deflection of 1.5 to 2 mm. Besides the normal galvanometer elements two groups of 6 high-frequency galvanometer elements are also included; one group, with peak sensitivity around 1,800 c and a d-c sensitivity of 1.2 mm per milliampere; the other, with a peak sensitivity around 2,800 c and a d-c sensitivity of 0.65 mm per milliampere. At frequencies above their peaks these elements have approximately the same sensitivities as do the low-frequency elements for the same frequencies.

The timing device consists of a 60-cycle elinvar tuning fork and a slotted shield rotated by a synchronous motor driven by the interrupted current from the fork. The accuracy is about 1 in 10,000 over long periods of time. Four types of timing marks are possible: 0.01- and 0.1-second fine lines across the paper and 1- and 5-second U-shaped timer deflection marks which can be imposed on any galvanometer trace. For very slow recording the 0.01-second lines can be blacked out.

Recording can be done at two speeds, "record normal" and "record slow," at the option of the operator at any instant. Assume that it is desired to record and determine the time between two events, 25 to 35 seconds apart. A paper speed of 25 cm per second is used and the record normal button is pushed. The operator observes the traces in the viewing slot and, as soon as the first event occurs, the record slow button is pushed which reduces the paper speed to about 5 cm per second. Shortly before the second event is due the operator

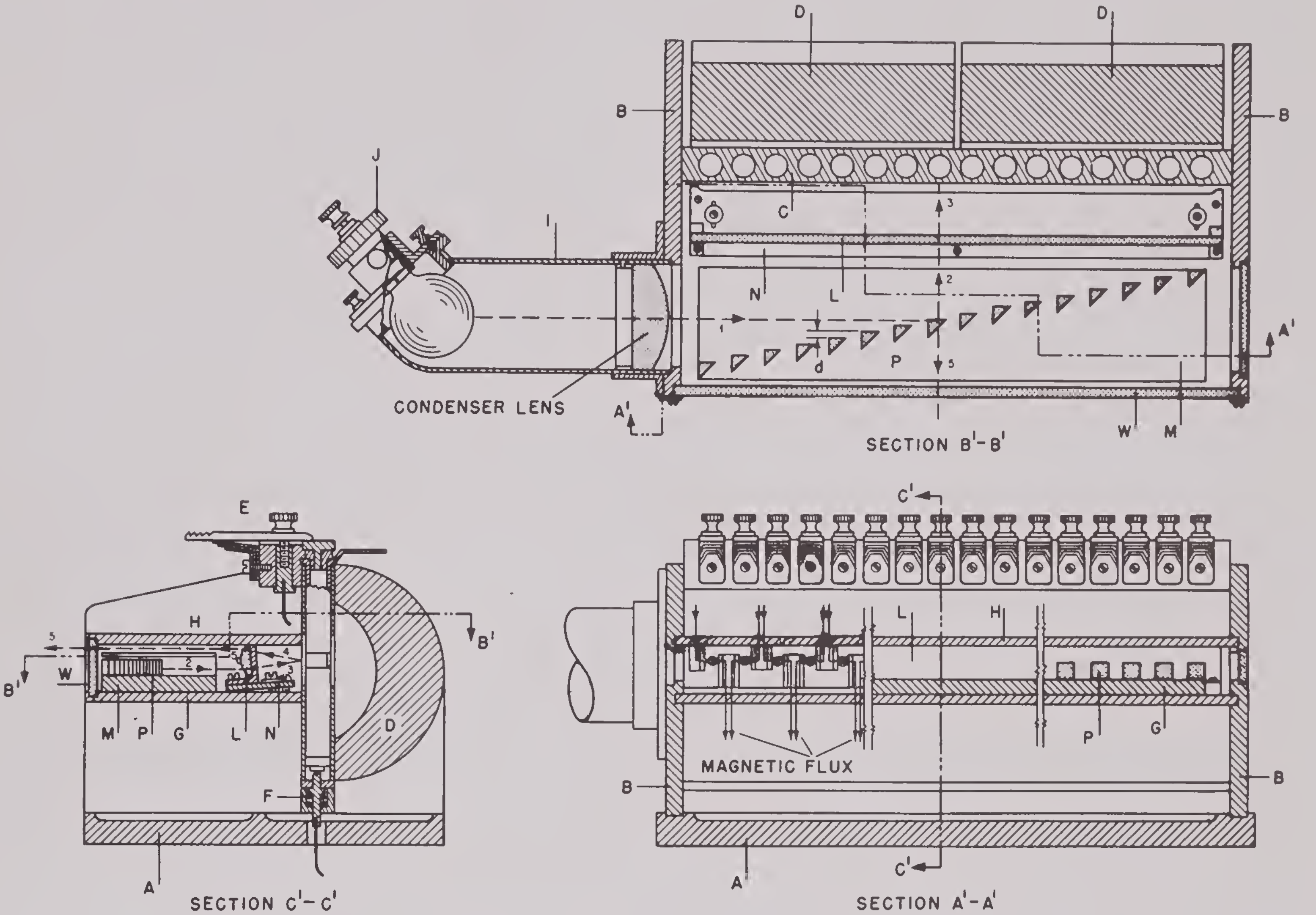

FIGURE 17. Diagram illustrating construction of multi-element moving-coil galvanometer.

pushes the record normal button and the event is recorded at suitable speed. The timing mechanism is operating during the entire record, with the result that the time determinations in the high-speed portions of the recording are unambiguous and are as accurate as though high speed had been used throughout the run.

It was originally planned to use light-sensitive cells to determine the time of burst for both on-the-ground and low-altitude explosions. In the method developed for this purpose, the light flash is picked up by photocells and recorded by the galvanometer after amplification. The amplifier is designed to be insensitive to slow changes in current due to changing light intensities resulting from clouds or other causes and thus gives a clear record of an explosion. A barrier-layer or generating-type cell is used and is effective at 2,000 ft or less. Experiments with spotting charges M1A1, M-3, and M-4 modified indicate that there is a lag of about 0.003 second between the detonation of the shot-gun shell in the charge and the bursting of the can. There are certain applications (other than sound ranging) where this might have to be borne in mind.

In connection with this light-sensitive device, microphones are used for seismographic ranging. Field amplifiers are placed at the observing stations, connected to the photocells and microphones, and wired to the trailer by field wires. A compact input box at the trailer permits the operator to use the field wires for telephonic communication with any observation station, or to check whether the telephone, photocell amplifier, or microphone amplifier is on a given line.

In later work the bombs being tested at Eglin Field were so increased in size that it was decided to drop them without explosives. When this was done, photocells and microphones were no longer usable since there was neither light nor sufficient noise. Geophones are used to register ground waves. These were installed at one of the test grounds and proved satisfactory for seismographic ranging in the absence of an explosion. The necessary techniques have therefore been devised for seismographic ranging with or without explosion.

The occurrence of an event in a plane is signaled from plane to trailer by means of a momentary interruption of a 1,000-c tone being transmitted over the plane radio. Installation of the necessary apparatus in a plane is simple and the use of the apparatus does not interfere with the normal use of the radio for communication. Seismographic experience has shown that the time of stopping a tone can be read accurately through interference or static which would make voice communication virtually impossible. The signal indicates either the "make" or "break" of a circuit. The opposite operation—closing a break circuit or opening a make circuit—gives no signal; hence, in using the signal it is immaterial whether the operation is momentary or permanent. After the tone has stopped for about 0.05 second, it gradually returns to its former amplitude, ready to indicate another make or break very shortly after the one from which it has recovered.

With this apparatus there was submitted a simple but adequate discussion of the principles of seismographic ranging, together with sample calculations made by least squares. A method of correcting for nonlinear propagation of sound in the immediate vicinity of an explosion was suggested. In addition there were supplied two very useful tables. One relates the velocity of sound in air to the temperature and the relative humidity. The other gives the value of a function involved in seismographic ranging for a wide range of variables. This table greatly reduces the work involved in computation of specific problems.

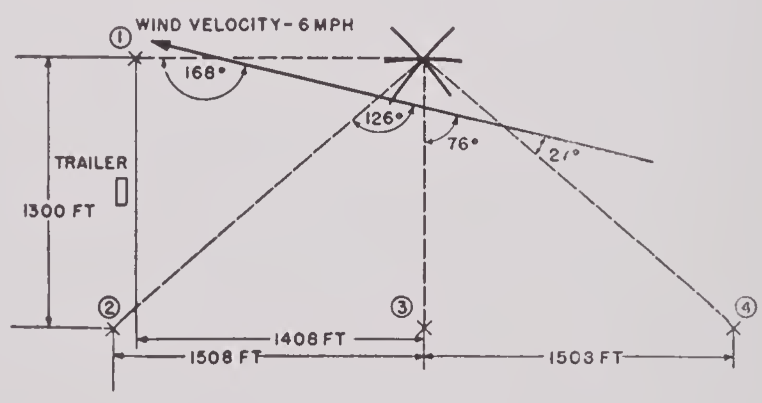

Figure 18. Range layout for experimental record shown in Figure 19.

Figure 18 shows an arrangement of the apparatus for a simulated field test. A microphone, a photocell, and an amplifier were placed at each of stations 1, 2, 3, and 4. The trailer was located midway between 1 and 2. Purely

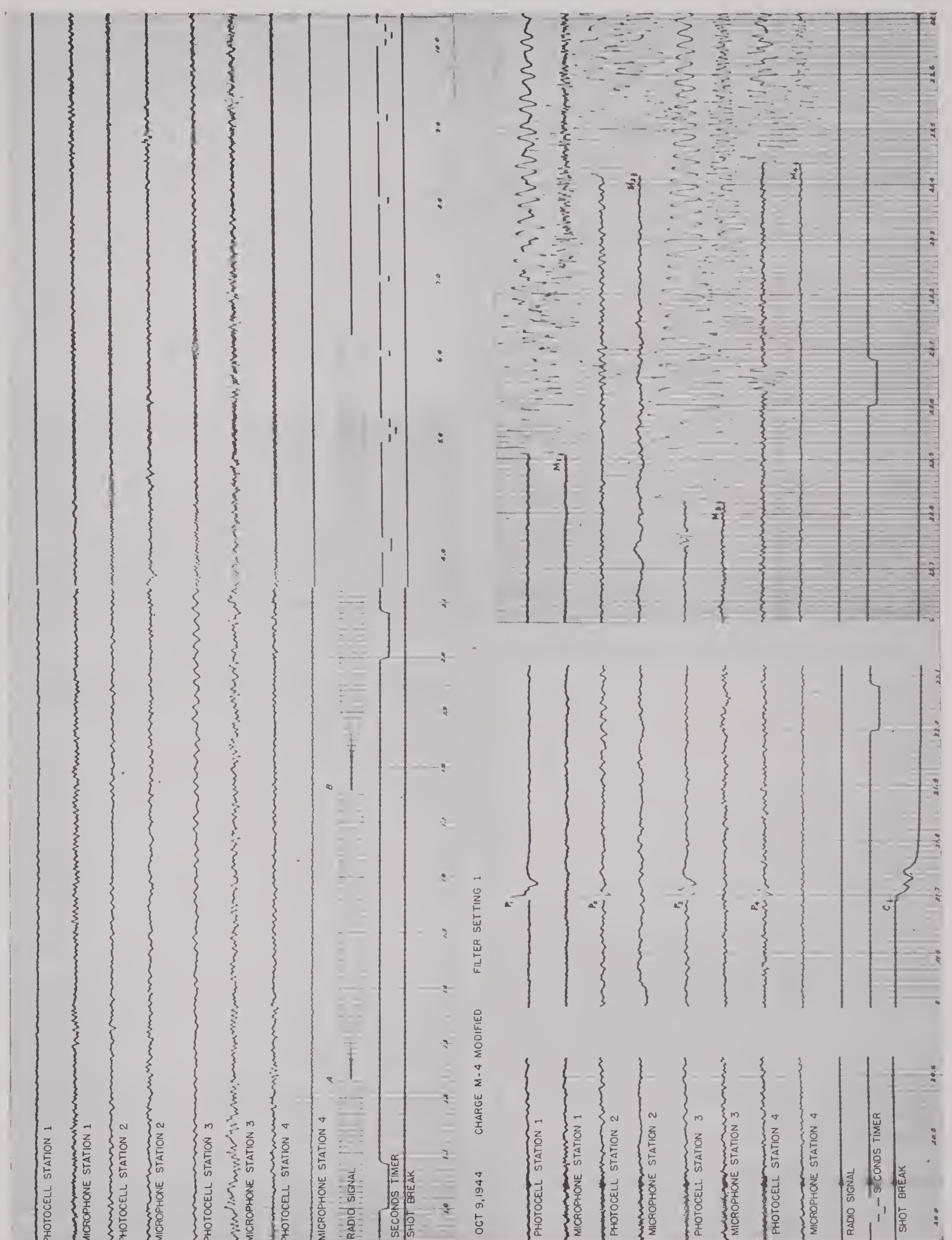

FIGURE 19. Specimen record taken with trailer equipment.

for test purposes the signal transmitter was placed 13 miles distant from the trailer. Its record is shown in the 9th trace, labeled "Radio Signal," on Figure 19. The first 8 traces record the signals from the photocells and microphones, the 10th, the record made by the timer. The 11th trace shows the breaking of a wire wrapped around the can by the exploding charge.

The charge was to be fired some 20 seconds after the second tone break which is shown at 1.758 seconds. After this break the record slow button was pushed; and a return was made to record normal about 20 seconds later. At 21.692 seconds the charge exploded, as is shown by photocell flashes $P1$, $P2$, $P3$, and $P4$, and by trace 11. Arrival of the sound at the microphones is indicated by $M1$, $M2$, $M3$, and $M4$, the times being respectively 22.907, 23.417, 22.823, and 23.438 seconds. In this connection, one of the points requiring greatest care in the analysis of a record is the determination of the initial microphone breaks. Calculations made with these data indicated the shot to have occurred at $x = +0.3$ ft, $y = +1296.6$ ft based upon station 3 as the origin of coordinates. The surveyed location was $x = 0.0$ ft, $y = +1298.0$ ft.

Chapter 5

HIGH-VOLTAGE X-RAY RADIOGRAPHY[a]

By *John A. Hornbeck*[b]

5.1 INTRODUCTION

Two projects for the investigation of X-ray radiography with extremely high voltages were initiated by Section D3, Instruments, of NDRC, one at the Massachusetts Institute of Technology [MIT] in the summer of 1941, and the other at the University of Illinois in January 1942. When these investigations were begun, high-voltage radiography in the range up to one million volts was gaining an established place in the production of ships, tanks, guns, planes, and other war matériel. The researches in *higher* voltage ranges were undertaken because it appeared that they might offer important advantages for radiography of objects of medium and large thicknesses (greater than 4 or 5 in. in equivalent steel thickness). Thus, the investigations were begun to ascertain the radiographic possibilities of extremely penetrating X-rays and to develop techniques for their use.

Each investigation was built around a specific machine or device for generating high-voltage X-rays. At the University of Illinois this device was the betatron, which had been designed and developed previously by D. W. Kerst. At MIT it was the electrostatic generator, which had been developed previously by R. J. Van de Graaff. Each of these machines constitutes a method of accelerating electrons to very high velocities. X-rays are electromagnetic radiations like visible light but of very much shorter wavelength and are produced by the collision of these high-energy electrons with a metal target. X-ray radiographs, or pictures, are made when a beam of X-rays passes through a dense object (such as a metal casting) and impinges upon a photographic film. In passage through the object the X-ray beam undergoes selective absorption, i.e., the thicker portions of the object absorb more X-radiation than do the thinner portions. Accordingly, on reaching the film the X-ray beam, which may be assumed to have been uniform originally, varies in intensity over its cross section. The detection of this variation of intensity by the photographic emulsion results in an X-ray radiograph.

A betatron and its control panel are shown in Figures 1 and 2. A production-type betatron X-ray generator installation is shown in Figure 3. In a betatron electrons are given energy by the accelerating effect of a changing magnetic field. A toroidal (doughnut) vacuum tube is placed between circular, specially shaped pole pieces of a laminated, a-c magnet which is operated at a frequency of 180 c. Electrons are injected tangentially from a "gun," which is placed within the tube, shortly after the magnetic field has passed through zero. As the field increases the electrons are accelerated around the tube, gaining an average of about 65

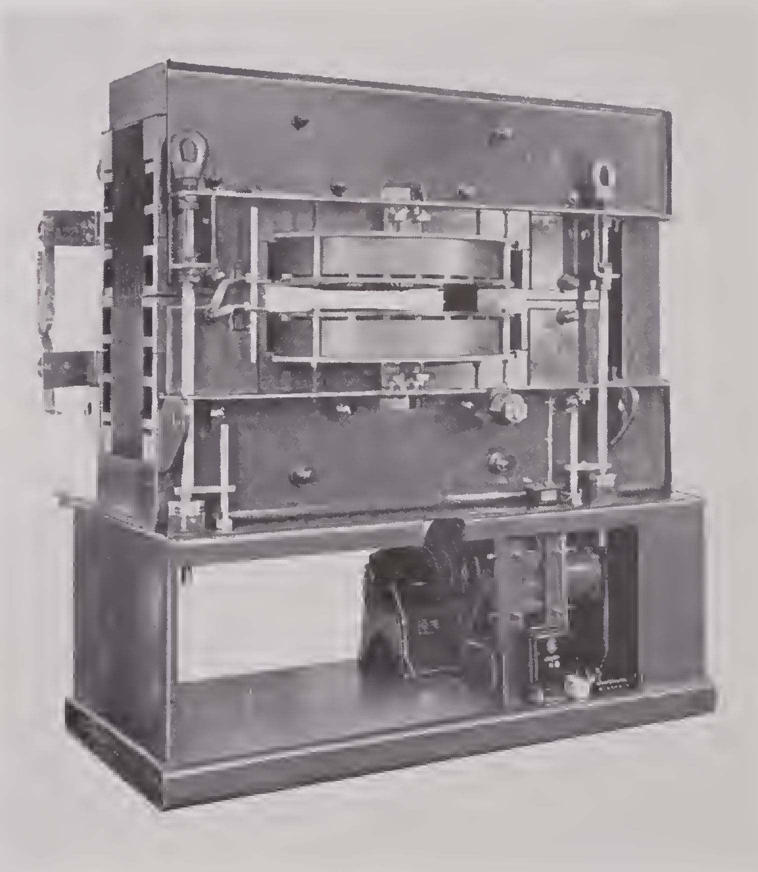

FIGURE 1. 20-MEV betatron magnet.

[a] OD-148, NO-123.

[b] Bell Telephone Laboratories.

FIGURE 2. Betatron control panel.

electron volts [EV] of energy on each revolution in a 20-million electron volt [MEV] machine. In obtaining their high energies the electrons make tens of thousands of revolutions through the tube in the one-quarter cycle during which the magnetic field is increasing. The magnetic field is so distributed that the electrons are focused into a very fine beam and brought to a circular path called an equilibrium orbit. After one-quarter cycle the magnetic field reaches its maximum, and the electrons attain their maximum energy. At this stage the field conditions that hold the electrons in an orbit are artificially upset, and the electrons are brought to the target where X-rays are produced. The X-rays emerge from the doughnut in a narrow cone in the forward direction. Because of the a-c excitation of the magnet the X-ray beam from a betatron is a pulsating one. In these two respects the betatron beam differs from that of the electrostatic generator. In the case of the latter, X-rays are radiated throughout the entire solid angle about the target, i.e., 4π; furthermore, the beam intensity is constant with time, i.e., not pulsating.

The electrostatic generator, as operated for producing X-rays, is fundamentally a conveyor system for carrying negative charge from the ground to an insulated conducting terminal or sphere. The difference in potential between the conducting sphere and ground depends upon the total charge deposited. This device is shown schematically in Figure 4. Figures 5 and 6 are photographs of the open generator, the X-ray tube and the control panel. In practice, a motor-driven, endless belt of insulating material runs between a pulley inside the sphere and a pulley at ground potential. Negative charge is deposited on the moving belt by corona from a row of sharp needle points, which are maintained at a negative potential opposite the grounded pulley, the potential being established usually by a transformer-rectifier set. The belt carries the charge to the top pulley. There the charge is extracted by another set of needle points and flows to the conducting sphere or terminal. The potential difference due to this charge accumulation is maintained across the electrodes of a special, highly insulating X-ray tube. This tube is conventional in the sense that it contains a heated filament which supplies the electrons that are accelerated toward the anode or target, the tube current depending solely on the thermionic emission at the temperature of the filament. X-rays are formed by the impact of the accelerated electrons on the gold target in the

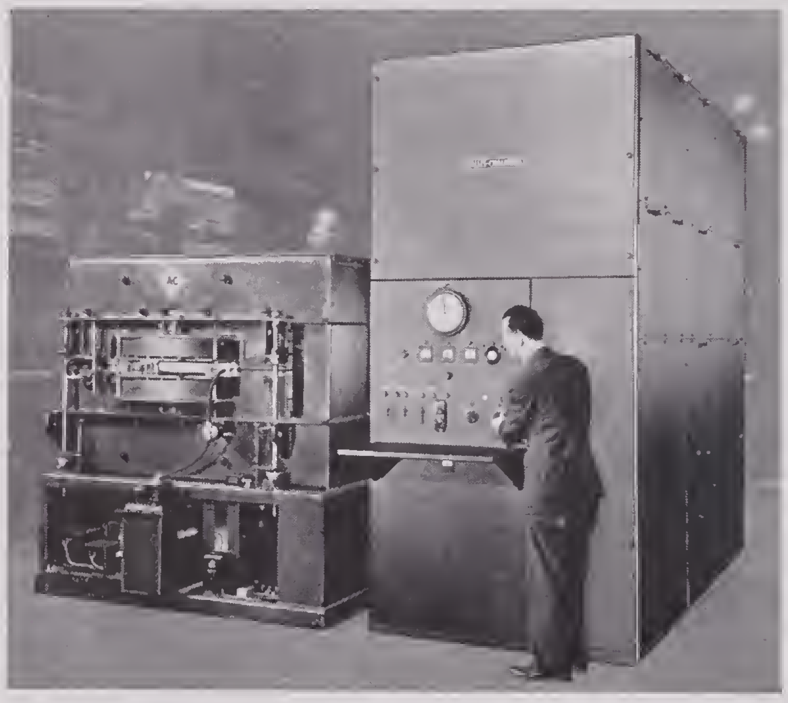

FIGURE 3. Production-type betatron X-ray generator installation.

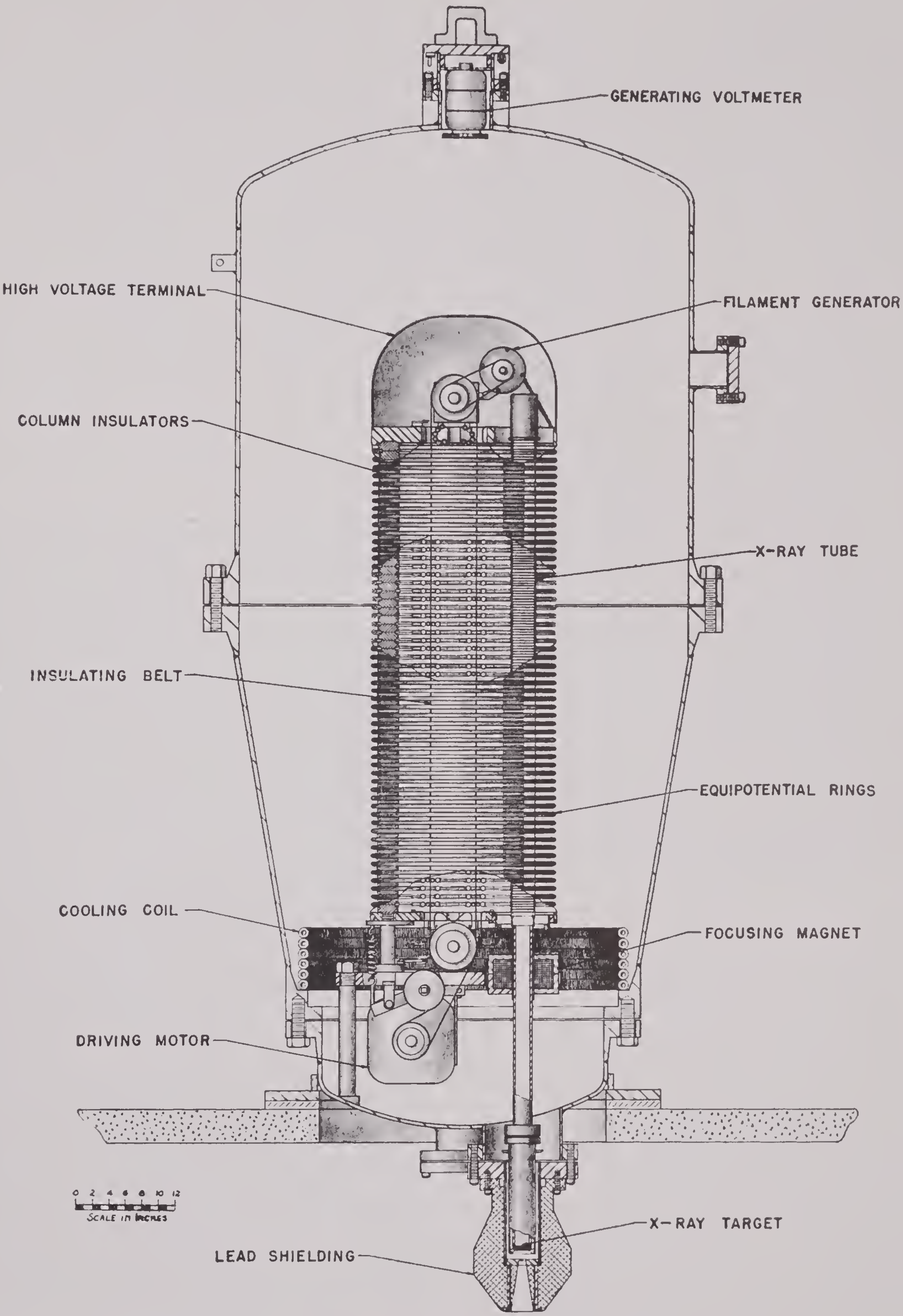

FIGURE 4. High-voltage X-ray generator.

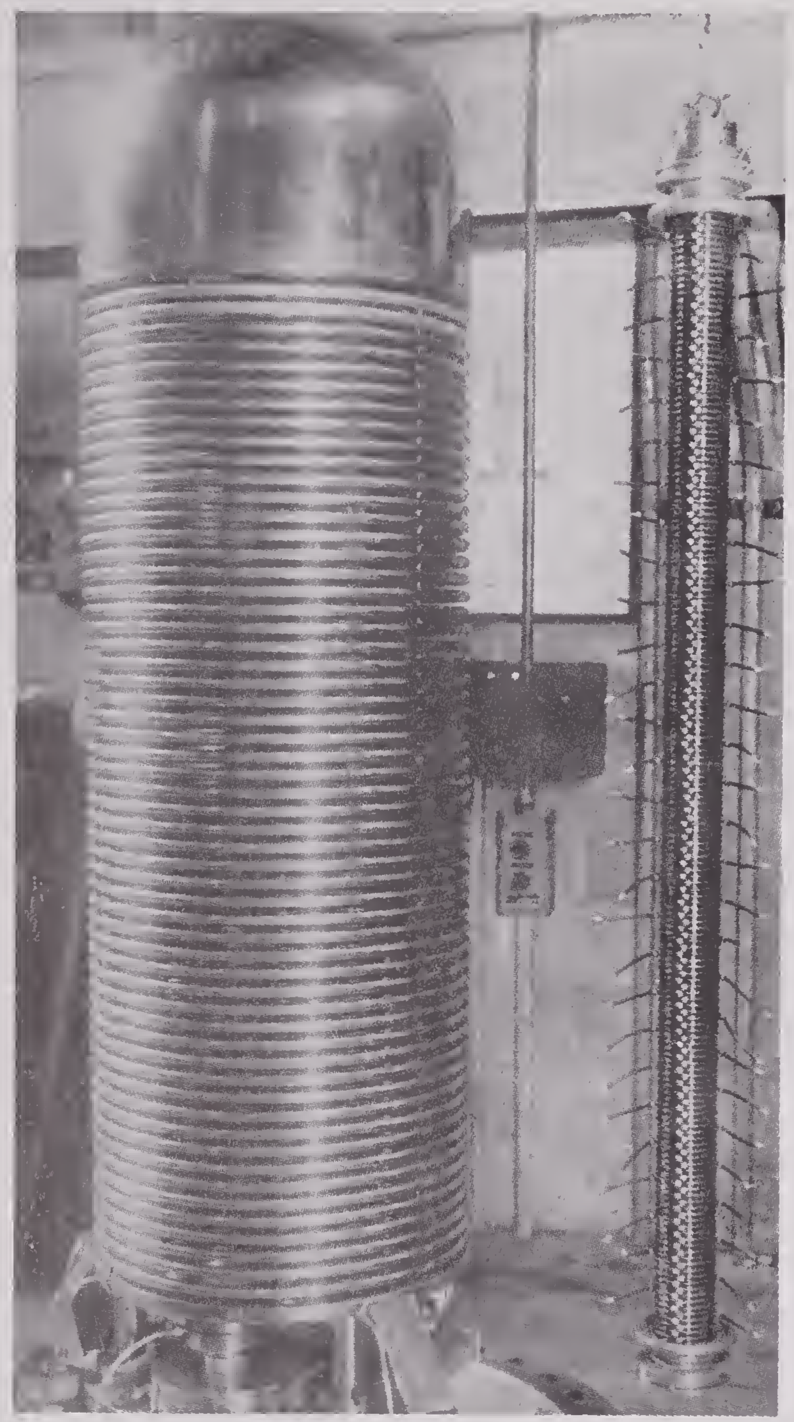

FIGURE 5. Electrostatic generator and X-ray tube.

tube. In steady-state operation the charging current to the terminal (conducting sphere) equals the X-ray tube current plus leakage[c] and corona losses between the high-potential parts and ground. In practice, the upper limit on the potential difference obtainable is set by the dielectric strength or insulation resistance between the high-voltage parts and ground. In order to improve the dielectric breakdown strength, compact generators are operated at a gas (usually air) pressure considerably above atmospheric (200 psi in the NDRC generators).

[c] A controlled leakage is introduced for increased stability and other purposes.

The consequence of the use of two different means of generating high-voltage X-rays was that two quite different wavelength bands were studied by the NDRC contractors. With the betatron the voltage range examined was from 3 to 20 million volts [MV], whereas with the electrostatic generator the voltage range was from 0.5 MV to 2.5 MV. The interactions between matter and the X-rays differed for the two voltage ranges. In the range up to 2.5 MV, the two most important X-ray absorption processes are the Compton effect and the photoelectric effect. Pair production does not enter the picture below 1.0 MV, and it is still a small effect at 2.5 MV. At higher voltages, however, pair production becomes rapidly more important, with the consequence that iron, for example, is least opaque to X-ray quanta of about 7-MEV energy. It should be apparent

FIGURE 6. Control panel for electrostatic generator.

that radiography in the voltage ranges mentioned here is quite different from that carried on at ordinary commercial voltages (say 200 to 400 thousand volts) where the photoelectric effect is predominant.

It is important to remember that the X-rays produced by any generator have a *continuous* distribution in energy. Two characteristics of the spectral distribution should be noted particularly. (1) The highest radiation energy produced is definite, corresponding to the voltage across the X-ray tube, i.e., to the maximum energy of the electrons striking the target. The well-known equation relating tube voltage, V, and the maximum X-ray energy $E_{\max}$ is

$$eV = E_{\max}, \tag{1}$$

where e is the electronic charge. The energy of an X-ray quantum is related to frequency and wavelength by the following expression:

$$E = h\nu = h\frac{c}{\lambda}, \tag{2}$$

where h is Planck's constant, λ is wavelength, and c is the velocity of light. From the above equations it may be shown that the tube voltage by fixing the maximum energy determines a maximum X-ray frequency ($\nu_{\max} = eV/h$) and a corresponding minimum wavelength ($\lambda_{\min} = hc/eV$). (2) Although all energies up to the maximum are present, the maximum *intensity* is concentrated in an energy band which occurs at approximately $\frac{2}{3}V_{\max}$. The practical significance of this is that a radiographic image results more from this important band of energies than from the X-rays of highest energy.

In all radiographs, irrespective of the voltage of the incident beam, the clarity of the image in the photographic emulsion is reduced by the effect of secondary or scattered radiation. In each of the three processes by which high-energy X-rays are absorbed (photoelectric effect, Compton effect, and pair-production) secondary X-rays and/or electrons are produced which are always of less energy than the primary quanta of radiation. The secondaries move off, in general, at an angle to the direction of the primary rays and therefore tend to blur the radiographic image formed by the transmitted primary or direct rays. This scattered radiation varies with the energy of the primary quanta and with the type of absorption process involved. In general, the higher the primary energy the more nearly straightforward the secondary radiations move, and hence the less deleterious the effect of the scattered radiation. This statement is completely at variance with the recommended techniques for low-voltage radiography, in which the lowest voltage possible is recommended as giving the least effect from scattered radiation. Both statements are true and compatible because: (1) in low-voltage radiography the photoelectric effect is predominant and the scattering decreases with tube voltage; (2) at higher voltage the other effects come into play and the net result of the three is that the scattering decreases with increasing voltage. It is therefore obvious that as the voltage of the incident X-rays is increased the harmful effects of scattering pass through a maximum at some voltage which is known to lie somewhere between 0.5 and 1.0 MV.

The three absorption effects enter in such a way that for each material there exists an optimum voltage for penetration, i.e., least opaqueness. This is one reason why there is an upper voltage limit for practical radiography. As the primary energy is increased beyond the absorption minimum some of the secondary or tertiary scattered X-rays become more penetrating than the primary. Less clarity of image results when this effect becomes too strong. From the investigations undertaken, a 20-MV X-ray source does not appear to have reached the upper limit which seems likely to be at 30 to 40 MV. The optimum tube voltage will probably vary also with the atomic number of the specimen, since the voltage for minimum absorption varies with this quantity, being higher for steel than for aluminum.

In everyday practical radiography it is required to obtain a good-quality radiograph in a reasonable exposure time. For a given thickness of specimen, the exposure time is governed by the X-ray output of the generator and the voltage at which it is operating. The clarity of the radiograph may be expressed in terms of a number of variables: latitude, definition, sensitivity, and contrast. These factors, in turn,

depend upon the type of X-ray film used and its processing, the voltage of the incident X-ray beam, the physical size of the focal spot, the geometry of the specimen, and the geometry of the experimental setup (i.e., target-specimen distance and specimen-film distance). It was the plan of the NDRC projects to evaluate quantitatively the effects of these variables on the quality of the radiograph and the exposure time within the voltage ranges mentioned. If the advantages resulting from the use of high voltages for radiography were significant, it was further planned to design and construct generators which could be used in the war program. As a result of the NDRC work, the techniques of high-voltage radiography were thoroughly examined and a number of machines of both types were delivered to and placed in use by the Armed Services.

5.2 ADVANTAGES OF HIGH VOLTAGE FOR X-RAY RADIOGRAPHY

An examination of the factors involved in radiography, mentioned above, brings out the advantages of high-voltage X-rays.

The radiographic method is employed for the examination of flaws within an object or specimen. The ability of a radiographic technique to do this for a particular object is measured by the smallest flaw which can be observed. This is expressed quantitatively by *sensitivity*, defined to mean the minimum percentage change which is observable in the total thickness of an object. For example, a 2 per cent sensitivity means that a flaw equal in thickness to 2 per cent of the total object thickness is just discernible. A smaller flaw is not observed. Thus *low* sensitivity means *good* sensitivity. Another important measure of the quality of a radiograph is the *definition*, defined to mean the ability to perceive detail. Although definition and sensitivity are related, it does not follow that if the sensitivity is good (low in value) the definition is sharp, or vice versa. When both the sensitivity and definition have optimum values the radiograph is of good quality. In addition, practical considerations demand that the *exposure time* be of a short, controllable length, and that the *number of exposures* needed to radiograph an object completely be as small as possible. This latter requirement depends upon the thickness which can be examined significantly by one exposure for a given exposure time. This thickness is called the *latitude*.

5.2.1 Exposure Time

The exposure time t and the exposure E are determined by the X-ray tube current, i, the decrease of the intensity of the incident radiation with increasing steel thickness (a function of X-ray energy), the intensity of the incident radiation, and the sensitivity of the detection instrument. In this case the detection instrument is the emulsion of the photographic film. Of the variables mentioned, the one principally important to exposure time is the decrease of intensity of the incident radiation with increasing steel thickness. (This statement will be qualified later.) This is a consequence of the exponential absorption of X-rays by matter, the equation for which is

$$I_x = I_0 e^{-\mu x} . \tag{3}$$

In the above, I_0 = the intensity of the incident X-ray beam; I_x = the intensity of the same X-ray beam after it has passed x units of length along its path through the metal or specimen; μ = the absorption coefficient of the material involved; and e = the base of the Naperian logarithm system.

The diminution of intensity for a given thickness of material traversed depends sensitively upon μ. In general, μ is the sum of three components: the photoelectric effect, the Compton effect, and pair-production. μ varies with the energy of the incident beam and the atomic number of the absorbing material. It decreases rapidly from 0.5 MEV[d] to the neighborhood of 4 MEV, depending on the absorbing material. Beyond this point the change is less rapid with increasing voltage. The practical significance of the exponential absorption is shown by the following illustration. Suppose the problem is to radiograph a steel forging which is 14 in. thick. The actual exposure time required for

[d] MEV is a unit of energy and it therefore refers to a particular X-ray frequency or wavelength. MV is a unit of potential difference. Thus a 2-MV generator produces X-rays of energy up to 2 MEV.

making this radiograph with an electrostatic generator operating at 2 MV and 0.4-ma tube current was 4 hours. At 1 MV under otherwise similar conditions, the exposure time would have been 12 weeks, and at 0.5 MV the exposure time would have been about 500 years. With 200 milligrams of radium under these conditions, computations indicate than an exposure of about 5 years would be required. On the other hand, at 4 MV the calculation indicates that the exposure required for this forging would be about 1 minute. For X-rays produced by a 20-MV generator this exposure time would be slightly shorter, assuming the same initial X-ray intensity. (The incident intensity of X rays from a 20-MV betatron is less than that obtainable with existing electrostatic generators.) For radiographing iron and steel sections, the biggest gain is obtained by using voltages up to at least 4 MV. The practical consequence of this is that for radiography of heavy metal sections (8 to 16 or 20 in. of steel) the employment of high-voltage X-rays makes the difference between a practical and an impractical exposure time. In the example given it is clear that even at 1 MV, the prewar industrial limit, the exposure time would be far too long.

Both the betatron, operated at 20 MV, and the electrostatic generator, operated at 2 or 2.5 MV, give reasonable exposure times for thick metal sections. For the thickest metal sections, i.e., 12 in. and above, the 20-MV machine will give exposure times substantially less than those of the 2-MV machine. Actually exposure times for the two devices are about the same for 6 in. of steel, viz., 20 seconds. For thinner steel sections the electrostatic generator is faster, although this is of little practical importance since the exposure time for 6 in. is very short. For thicker sections the 20-MV betatron is faster. This comparison is made on the basis of an electrostatic generator operated with 0.3-ma tube current, and a 20-MV betatron with about 0.1-μa current. In both cases the target-film distance is 24 in., the film Eastman Industrial Type A developed 8 minutes at 68 F to a density of 1 above fog density. It should be noted that practical differences in exposure time occur only for steel thicknesses above 10 in., inasmuch as for this thickness the exposure time with the electrostatic generator, using Industrial Type A film, is a reasonable period of approximately 15 minutes, whereas that for the 20-MV betatron is approximately 2 minutes. The fact that for some steel thicknesses the low-voltage machine has a shorter exposure time than the high is readily explained by introducing another of the variables mentioned above, viz., X-ray output or incident intensity. The electrostatic generator may supply an X-ray tube current perhaps 300 or more times that obtainable with the betatron. Even though the production of X-rays is more efficient at 20 MV than at 2 MV, it still takes 5 or 6 in. of steel to permit the superior absorption coefficient for the higher-voltage radiation to take over.

5.2.2 Latitude

The latitude is determined by the decrease in the intensity of the radiation when the object thickness is increased, and by the end points of the useful density range on the film. This quantity is quite complicated, in that it varies considerably with the choice of film and with the choice of the system for viewing the film. For example, a high-intensity viewing system increases the useful density range of most X-ray film. It has been established, however, that the latitude in the range 0.5 to 2 MV increases with increasing voltage, being perhaps 80 per cent greater at the higher voltage. No comparable analysis has been made for the voltage range from 3 to 20 MV. The available evidence indicates that at 20 MV variations of 6 in. of steel thickness could be radiographed without significant loss of detail.

5.2.3 Definition

The definition is measured by the diameter of the disk, or circle of confusion, forming on the film the image of a point on the surface of the object or specimen facing the X-ray source. For a given radiographic setup this diameter is completely determined, except for film characteristics, by the size of the X-ray source, the cross-sectional diameter of which is usually referred to as the *spot size*. From the geometry

of a radiographic setup it follows that

$$\text{Definition} = \text{Spot size} \times \frac{\text{Distance from the top of object film}}{\text{Distance to top of object from X-ray source}}.$$

Since the definition is directly proportional to spot size, good definition demands an extremely small spot size. In both the betatron and the electrostatic generator spot sizes of maximum dimension no more than 0.010 in. were achieved in practice. This spot size may be compared with that of 0.25 in. available in commercial high-voltage X-ray generators (e.g., the resonant-transformer type).

The other factor upon which definition depends is the size of the area of the photographic film which is sensitized by a single X-ray quantum. Film grain size, of course, varies enormously with the result that the sensitized area may be smaller than the grain size of the film (though only for a small focal spot). Hence, the grain size essentially determines the resolution of the film and, therefore, sets the lower limit on definition.

It should be noted here that small focal-spot size and high definition are not exclusively attributes of high-voltage radiography. The focal-spot size depends upon the electron optics of the X-ray tube. It is easier to obtain a focused beam when there is not a wide spread in the energies of the electrons comprising the beam. Thus, in general, it is usually easier to focus a beam accelerated by a constant-potential source, such as an electrostatic generator, than one accelerated by a variable-potential source.

5.2.4 Sensitivity and Scattering

Sensitivity, as previously defined, is related to the smallest density difference perceptible on the film. This difference must correspond to a change in the *direct* radiation component of the total radiation; i.e., density differences due to scattered radiation are excluded. In fact, scattering increases the sensitivity (makes it worse). At 2 MV the sensitivity decreases from approximately 0.50 per cent at 3 in. of steel to 0.41 per cent at 14 in. of steel. Over this range of steel thickness the sensitivity decreases faster than a straight line drawn between the end points mentioned above. The sensitivities at 0.5 MV and at 1.0 MV are approximately the same functions of steel thickness, decreasing from approximately 0.54 per cent at 3 in. to 0.47 per cent at 14 in. Thus at some voltage between 0.5 and 1.0 MV the sensitivity passes through a maximum (i.e., has its worst value). If a means is found (this will be discussed later) for preventing the scattered radiation from reaching the film, the sensitivity increases linearly with voltage. Thus, when scattering is eliminated, one should work with as low a voltage as is feasible. When scattering is present, the sensitivity also depends rather critically on the geometry of the radiographic setup. Thus with one radiographic specimen it may be inherently impossible to obtain as good quality using good techniques as it is with other geometrics.

With the 20-MV X-ray machine it has been found that the minimum detectable thickness is almost independent of object thickness and of the position of the flaw within the object. Thus, at this voltage the sensitivity decreases (becomes better) linearly with increasing object thickness. This is a consequence of the fact that at this high voltage there is relatively little scattered, or secondary, radiation reaching the photographic plate. Quantitatively, at this voltage with Type A film, a 1 per cent sensitivity has been obtained at 3 in. of steel thickness, and a 0.21 per cent sensitivity at 14 in. thickness.

In terms of scattering the advantages of the 20-MV radiation over that of lower voltages may be expressed quantitatively by a figure of merit called the "scattering factor." The scattering factor is defined as the ratio of the scattered radiation present to the radiation in the direct beam at any given depth of penetration. After passing through 4 in. of steel the scattering factor is 0.2 for 20 MEV, 0.7 for 10, 4.0 at 2, 7.0 at 1, and even larger at 0.5 MEV. The experimental method of measuring the scattering factor at 10 and 20 MEV is open to some question, however.

There are practical ways (e.g., use of the Potter-Bucky diaphragm and "backing away") of reducing the adverse effect of scattered radiation in some voltage ranges, but only at the expense of increased exposure time. In the

radiography of especially thick objects, exposure time requirements preclude the use of these techniques. Where exposure time was not a limitation, use of a Potter-Bucky diaphragm (illustrated in Figures 7 and 8) yielded amazingly good sensitivities at 2 MV by reduction of scattered radiation, particularly in setups where the geometry of the object was such that the scattering effect was pronounced. A similar diaphragm designed for use with a 20-MV generator was found to offer no improvement in scattering factor. This may be attributed to (1) the fact that less scattered radiation is

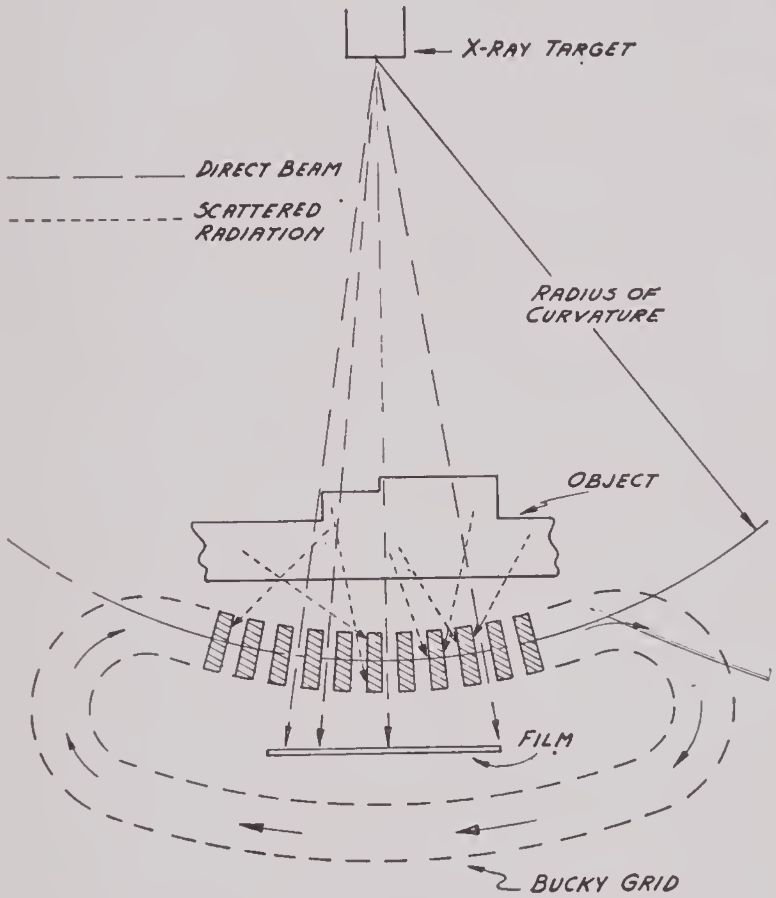

FIGURE 7. Principle of operation of Potter-Bucky diaphragm.

present at the higher voltage and (2) the fact that radiation which is scattered at the higher voltage is deviated through such small angles that it cannot be easily removed by a Potter-Bucky diaphragm.

5.3 SUMMARY OF WORK

5.3.1 X-Ray Radiography Work with the Betatron[e]

In January 1942 work was started on the study of the radiographic properties of X-rays in the energy range between 3 and 20 MEV. Such X-rays were readily produced by the betatron, and the main initial purpose of the work was to ascertain and improve the value

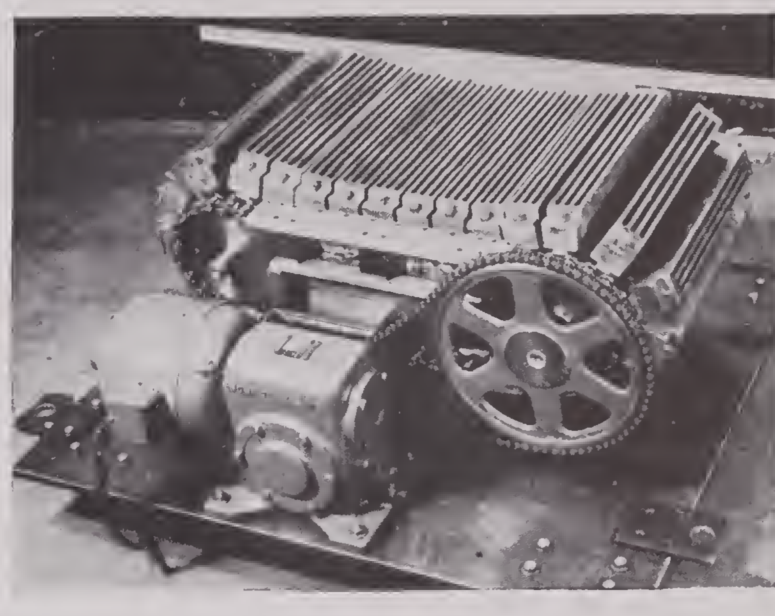

FIGURE 8. Potter-Bucky diaphragm.

of the betatron for practical radiography. Work with the betatron was continued until July 30, 1945.[1-18]

The work performed can be subdivided into 2 main headings: the design and improvement of the betatron for radiographic purposes, and the investigation and development of radiographic properties and techniques of high-voltage X-ray radiation. The major results of the work may be classified in 5 groups.

1. From a study of the nature of high-energy radiation and of the radiographic characteristics of the betatron, it has been established that the 20-MV betatron is useful for a wide range of radiographic problems and that its X-rays are exceptional in radiographic quality and speed for thick metal sections (6 to 20 in.). This part of the work included a study of the high-energy X-ray characteristics of many types of film.

2. A number of important improvements have been made in the 20-MV betatron which have increased the X-ray yield, have improved the mechanical and electrical stability and have simplified operation and maintenance of the machines. A 4-MV machine which is portable and quite simple to operate has been designed.

3. At the University of Illinois three complete machines of the 4-MV size were built, of which two were put in use elsewhere. Two

[e] OD-148.

20-MV machines were completed and put into operation. These were manufactured largely by the Allis-Chalmers Manufacturing Company, Milwaukee, Wisconsin, under an NDRC contract, according to designs and specifications drawn up with the help of University of Illinois personnel. The University of Illinois personnel installed and tested the 20-MV machines as radiographic units. They also cooperated with the Naval Research Laboratory, Anacostia, D. C., in the manufacture and initial operation of a third 20-MV machine.

4. Sealed-off glass and porcelain betatron vacuum tubes, or doughnuts, in sizes suitable for the 4-MV and 20-MV betatrons were developed and small-scale manufacturing problems in connection with them were solved.

5. The original betatron at the University of Illinois has been applied to radiography of numerous specimens submitted by the NDRC and other government agencies.

5.3.2 X-Ray Radiography Work with the Electrostatic Generator[f]

Work with the use of the electrostatic generator for high-voltage radiography was begun in the summer of 1941 and was concluded in June 1945.[19-23] The initial purpose of this project was to investigate the radiographic quality of high-voltage X-rays, to develop techniques for the use of a 2-MV electrostatic generator and to prepare designs of such a generator suitable for Service and industrial use. Five complete generators (four at the expense of the Navy) were constructed under NDRC contract. The first of these units was installed at a Navy field station in May 1943. A second was shipped to another Navy station in November 1943. The third unit was completed shortly thereafter, but was not shipped until March 1945 because of a delay in building construction at the Navy station to which it was assigned. A fourth unit has been delivered to the Navy. In accordance with the purpose for which it was planned, the fifth unit was used at MIT for testing and development work in connection with the operation and improvement of the other four units.

In addition to the design work there was undertaken a very intensive experimental and theoretical investigation of the radiographic properties of X-ray radiation in the voltage range from 0.5 to 2.5 MV. A quantitative examination of the increase of X-ray exposure with steel thickness at various voltages was made with the use of X-ray film and with sensitive radiation-detection devices. The scattering of high-voltage X-rays was studied from both theoretical and experimental points of view, with the result that clear understanding of the phenomena has been obtained. From this research has come the development of radiographic techniques to minimize the fogging effect of scattered radiation on the film. In the exploration of 2-MV radiography and in the research-development of new radiographic techniques for use in the field, about 5,000 radiographs were made. These were not only of test objects, but also of a large variety of objects of special radiographic interest. Some of these were of prime importance to the war effort and were sent from various places to MIT because they could not be radiographed with lower-voltage equipment available elsewhere. One of the most important developments associated with the project has been the X-ray tube built by the Machlett Laboratories, Inc., with collaboration by MIT in design and testing. Although the tubes now in use are continuously evacuated by a pumping system a sealed-off tube was supplied by Machlett toward the end of the project, which successfully passed various tests including 50 hours of operation at 2 MV. Extensive research on various other aspects of the generator was conducted to improve the performance of the machines in the field. Attempts were made to improve the insulating charging belt, the resistors, the insulators, and to test the use of gases other than compressed air (e.g., SF_6) for insulation.

5.4 EVALUATION

These high-voltage radiography projects made a real and important contribution to the war effort. The delivery of high-voltage X-ray machines to the Army and Navy is one indication. The first 20-MV betatron constructed by Allis-Chalmers Manufacturing Company was

[f] NO-123.

delivered to the Manhattan Project in the summer of 1944. A second, similar machine was delivered to the Rock Island Arsenal, Rock Island, Ill., in February 1945. The first 2-MV electrostatic generator was delivered to the Bureau of Ordnance, Navy Department, in the spring of 1943, and has been in almost continuous use since then at their Explosives Investigation Laboratory, Stump Neck, Md. The second electrostatic generator has been in service on the West Coast since the end of 1943. In addition, the NDRC contractors operated their generators on occasion for radiographing war equipment.

These investigations have important applications for postwar industry inasmuch as they have opened up, for the first time, the field of X-ray radiography above 1 MV. The advantages of the use of voltages above this figure have already been pointed out. Not only have machines been constructed and demonstrated to be practical for industrial usage, but the theory and experimental techniques involved in high-voltage radiography have been worked out in a commendable fashion.

The following general statements can be made concerning the use of the betatron and the electrostatic generator for radiographic purposes. There are certain basic advantages connected with the use of the higher-voltage betatron. The radiation produced by the large betatron is better for radiography principally because there is less scattering associated with it, because wider film latitudes result and because somewhat thicker specimens can be radiographed with reasonable exposure times. Since the betatron is mechanically simpler than the electrostatic generator there is probably less chance of a breakdown interfering with the operation of the former. However, an electrostatic generator operating at 4 MV (the higher voltage being made possible by use of a better insulating gas) would probably be superior to the 20-MV betatron in exposure time for even thick sections. Tentative designs for this higher-voltage electrostatic generator were worked out under the NDRC contract. In evaluating the projects the most important point to be kept in mind is that both machines are definitely superior to available commercial apparatus in regard to both quality of radiography and exposure time.

Practical application of the small 4-MV betatrons (one of which was delivered to the British and the others to the Navy) is open to some question. Their X-ray output is small and does not compare with the outputs available from the 20-MV betatron and the 2-MV electrostatic generator. For the radiography of some metal sections not over 5 in. thick they may have application, since up to this thickness the exposure times are not excessive (one hour for 4 in. of steel), and the quality of the radiograph should be better than that obtained with lower-voltage equipment with relatively large focal spots.

Both these projects carried on extensive investigations of the theory and application of high-voltage radiography. These researches resulted in information of importance not only in radiography and applied physics but also in pure scientific knowledge.

Chapter 6

BOMB INSTRUMENTATION[a,b]

By *F. L. Yost*[c]

6.1 INTRODUCTION

The importance of air warfare made it necessary to improve bombing tables and to extend them to cover high-altitude bombing. Aberdeen Proving Ground, which was concerned with making such bombing tables available to the Army Air Forces and which was conducting an extensive experimental program on bombing, requested the development of a device which would indicate the retardation experienced by a bomb during its flight.[a] During the development of this device, Aberdeen Proving Ground further requested[b] that an investigation be made of the feasibility of using standard seismic detectors for determining the time and position of bomb impact (no explosion involved) on the ground in connection with range bombing.

6.2 MILITARY REQUIREMENTS

The original request[a] was for the development of two instruments. One was to determine the time of impact of a falling bomb on a time scale coordinated with its time of release from the plane. It was suggested that the device should consist of a low-powered high-frequency radio transmitter mounted in the bomb, a switch for turning on the transmitter shortly after the time of release and a receiving apparatus for converting the signal into suitable form for recording on an oscillograph. The other device was to measure the retardation of a falling bomb due to air resistance. It was suggested that the device consist of a one-component accelerometer to be mounted in the bomb and so designed that its readings could be transmitted by radio to a ground station. No specification was made of the accuracies desired in these instruments. However, as they were needed to supply data applicable to the computation of bomb trajectories, especially for bombs released at high elevations, it was clear that as high accuracies as possible were desired. Actually, one instrument was developed which sufficed for both requirements.

The request[b] for studying applications of seismograph equipment for determining time and position of bomb impact was not specific as to results expected. It merely asked that the possibilities be investigated.

6.3 SUMMARY OF DEVELOPMENT

The work on this project was done by the Gulf Research and Development Company. For determining the retardation of a falling bomb, there was designed for installation in it a small accelerometer and a radio transmitter;[1-4,6,7] the combination transmits to a ground station an audio frequency dependent upon the retardation being experienced by the bomb. The mean density of the unit is very close to the density of the explosive it replaces, and thus it does not alter the normal ballistics of the bomb. Units are made in two lengths: one for installation in either 500-lb or 1,000-lb bombs and the other for 2,000-lb or 4,000-lb bombs. This allows two standard sizes of units to accommodate four sizes of bombs without the accelerometers being more than 11 in. from the center of mass in any case.

In flight a bomb has a slight vertical angle of attack between its axis and the tangent to its trajectory, and undergoes oscillations in pitch and yaw about its center of mass. An accelerometer mounted at the bomb's center of mass and aligned with its axis indicates not the total retardation, but rather the retardation multiplied by the cosine of the angle the axis makes with the tangent to the trajectory. In its final design, the apparatus permits measurement of bomb retardation continuously during flight to an accuracy of about 1 per cent of g

[a] OD-90.
[b] OD-124.
[c] Technical Aide, Division 17, NDRC.

through the range 0 to g and measurement of the time of flight to 5 milliseconds.

The contractor's personnel assisted the Ballistic Research Laboratory, Aberdeen Proving Ground, in making a number of drop tests with 4,000-lb bombs, from which the drag functions suitable for construction of bombing tables could be deduced. The Ordnance Department procured from the contractor approximately 30 units for various sizes of bombs to use in connection with other bomb-ballistic studies. The method of computation of the trajectories from these data was worked out in the Ballistic Research Laboratory. Among the interesting results from these studies was the observation of the centrifugal forces introduced into the accelerometer by the yawing motion of the bomb. These studies also gave opportunity for observation of the magnitude of the dispersion (variation between bombs) in drag forces. It is expected that these accelerometer units will continue to be useful tools in bombing studies.

The contractor not only specified suitable seismographic instrumentation, as a result of tests, but also outlined the general methods of handling the information in deducing the time and position of the impact of a bomb in range bombing.[5,8] As a result, a seismographic detector installation was procured for the Muroc, Calif., bombing range and for two years it has been the mainstay of the instrumentation for determining time of flight.

6.4 DESCRIPTION AND TECHNICAL INFORMATION

6.4.1 Bomb-Retardation Device

Figure 1 is a block diagram showing the method used for measuring axial retardation of the bomb. Retardation is the difference between g and the actual acceleration of the bomb. The accelerometer generates an audio frequency (750 to 900 c) which is changed by the accelerating forces acting upon a suspended mass. This audio frequency modulates the signal of a radio transmitter (70 mc) which is radiated from an antenna composed of the bomb and a wire whip extending beyond the tail. The signal is detected and amplified in a commercial ultra-high-frequency radio receiver on the ground. It is then filtered to remove interference and mixed with a fixed-frequency audio signal to produce a low beat frequency. This beat frequency is recorded on a photographic tape controlled by a chronograph, from which the original audio frequency at any instant may be computed.

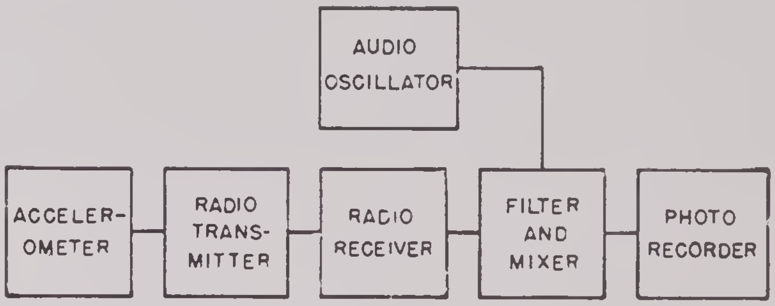

FIGURE 1. Block diagram showing method used for measuring axial retardation of bomb.

Subtraction of any beat frequency from that corresponding to zero retardation gives the frequency change resulting from the retardation; and the value of the retardation is determined from the calibration curve of frequency change vs retardation. A beat frequency is used because low frequencies are more easily recorded on a chronograph than high frequencies. The higher frequencies generated in the accelerometer are more easily amplified and filtered and they are also far enough above the 60-c recorder power and the 100- to 300-c microphonics of the radio tubes in the bomb to keep interference at a minimum.

To serve as an accelerometer, a steel plunger is suspended in the coils of a Hartley oscillator by spiral springs at either end. The springs permit motion of the plunger, relative to the coils, parallel to its own axis and the axes of the springs themselves; but they offer considerable stiffness to motion transverse to that direction. The springs have a linear stress-strain relationship through 3/8 in. of motion. The accelerometer is so mounted that the axis of the plunger is parallel to the axis of the bomb. Regardless of the attitude of the bomb when falling, the only thing which can cause a distortion of the springs is the retardation experienced by the bomb, the component of retardation along the axis of the bomb being the only part effective in causing distortion. For retardations involving accelerations from 0 to g the displacement of the plunger and the cor-

responding change in frequency of the Hartley oscillator are proportional to the retardation experienced. The accelerometer is arbitrarily built so that an increase in retardation causes a decrease in frequency.

The accelerometer transmitter is built around two 1G6 GT double triode tubes, as shown in Figure 2. One triode section is used for the antenna coil in the tank-coil field receives power from the tank circuit and, through a coaxial transmission line, delivers it to the whip and bomb.

The retardation-measuring unit is built with a large threaded bushing at the base of the antenna post, which fits into the fuse hole of standard tail plates. A large nut is screwed up

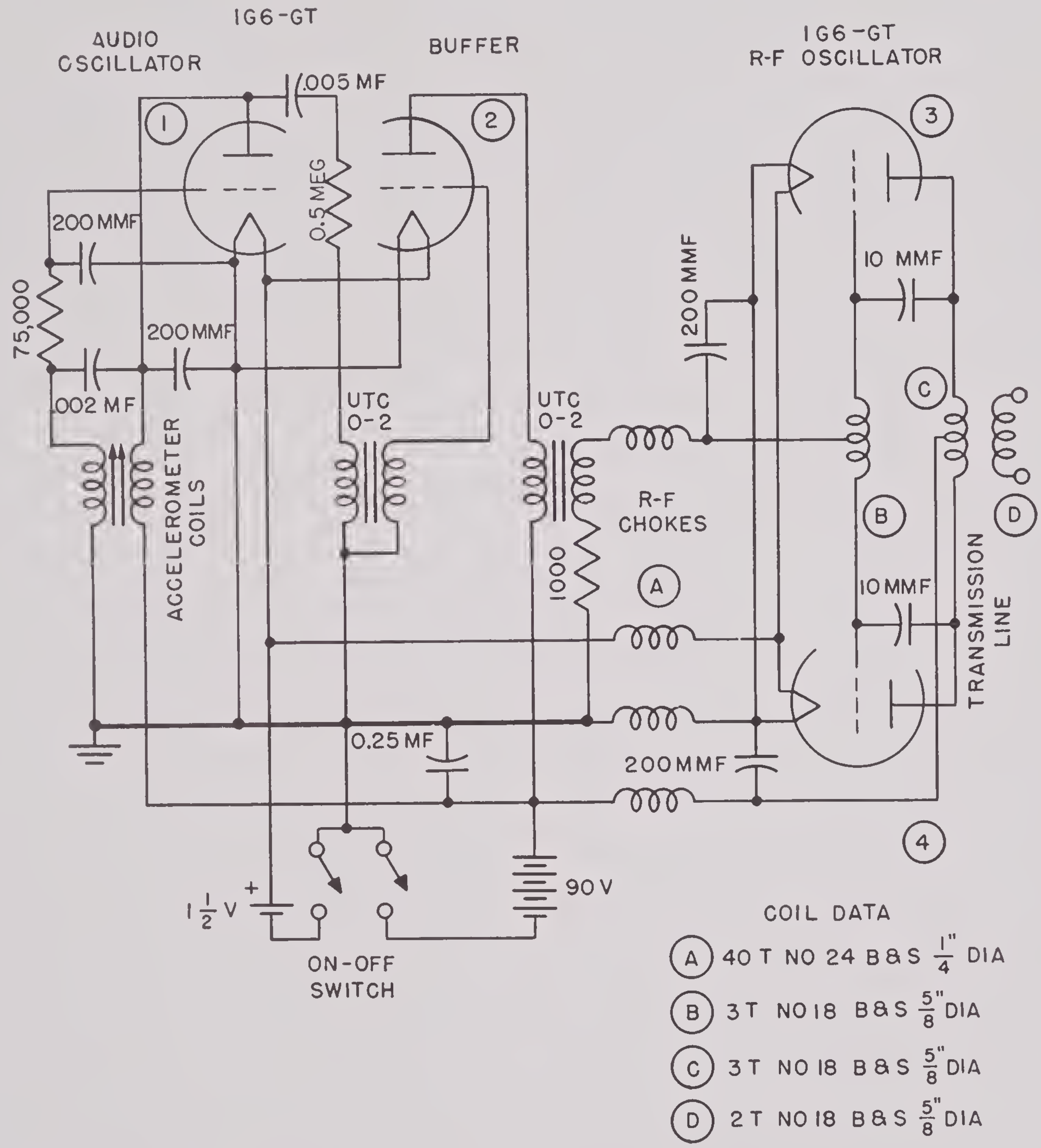

FIGURE 2. Wiring diagram of accelerometer transmitter.

Hartley oscillator accelerometer. Its plate is transformer-coupled to the grid of the second triode, which comprises the buffer stage. The other two triodes are connected in push-pull in an r-f tank circuit to form an r-f oscillator. The plate of the buffer stage is transformer-coupled to modulate the grids of the r-f oscillator. An tightly to secure it in place. This type of mounting allows units to be adjusted and calibrated before shipping; then at the bomb-loading shed they can be placed inside the bomb and packed in sand before the tail plate is attached. The design of this unit has all the advantages noted in the first paragraph of Section 6.3.

In order to determine the retardation associated with a given frequency change, the accelerometer must be calibrated. This is done by noting its audio frequencies when its axis is inclined at known angles to the horizontal. If θ is the angle between the accelerometer axis and the horizontal, the accelerating force f acting against the spring is $f = ma = mg \sin \theta$; and hence the "retardation" being experienced is $g \sin \theta$. Any retardation between $-g$ θ and g may be obtained by proper selection of the angle θ. In calibration there is sometimes a slight bowing of the curve of frequency change vs retardation due to transverse motion of the plunger. To correct for this, frequency readings are taken for steps of $0.1g$ from $-0.1g$ to $+g$, both up and down the scale. The unit is then rotated 180 degrees about its longitudinal axis and another similar set of readings is taken. The frequencies recorded for each acceleration position are averaged and plotted on graph paper against the corresponding acceleration or deceleration. The calibration graph for a normal unit is a straight line which passes through the origin, as shown in Figure 3.

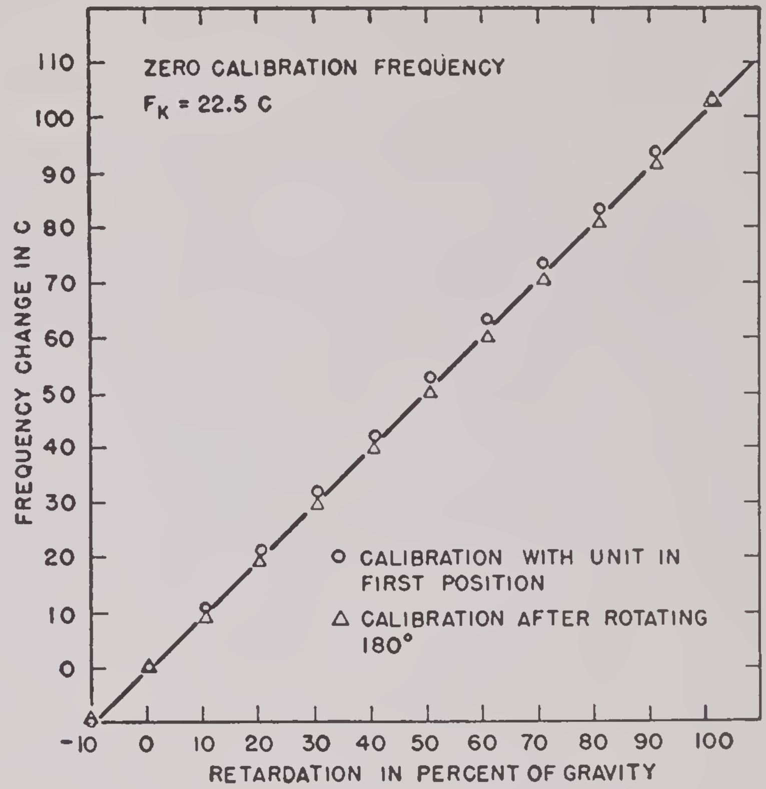

FIGURE 3. Calibration graph for normal unit.

In order to be certain that this method of averaging does not introduce or mask possible errors, an independent determination of frequency change vs retardation from 0 to g was made in a manner which involved no transverse loading (i.e., by a beam-loading method with vertical motion of the plunger). The procedures were found to be equivalent.

When data on retardations are collected it is the beat frequencies corresponding to various positions of the plunger which are recorded. If the calibration curve for the unit is known and if the beat frequency of some known acceleration can be recorded just prior to or during flight, the true retardation may be computed. In the final design of the accelerometer unit a solenoid was incorporated to pull the plunger against a fixed stop for zero calibration. The frequency difference F_k between the fixed-stop position and the zero retardation is determined by calibration; for example, F_k for Figure 3 is 22.5 c. During a test the beat frequency of the fixed-stop position is recorded just prior to release of the bomb.

Figure 4 is an assembly drawing of the accelerometer, showing the solenoid arrangement. When the solenoid is energized by a 6-v battery external to the bomb, the armature is pulled to the right until the head of the plunger engages the zero-calibration stop; when the solenoid is not energized, the armature is returned to neutral by a coil spring. The neutral position of the armature is toward the nose of the bomb, so retardation forces tend to aid the spring action rather than oppose it, thus preventing the armature from interfering with the motion of the accelerometer plunger during flight. The solenoid is attached to a brass plate the purpose of which is to conduct heat from the solenoid to the steel case. Without the plate there is danger that the hexane, which is used as a damping fluid in the plunger chamber, will boil, rupturing the housing, if the solenoid is energized for more than 10 minutes at a time.

The equipment which records the bomb's retardation is designed to give a continuous record of the signal transmitted by the accelerometer unit when a bomb is released at high altitude. The axial component of the retardation of the bomb can be found by measuring the change in frequency of the audio signal; the time of impact with the surface of the earth can be found by determining the time at which the transmitter signal fails; and the time of flight can be found by comparing the time of impact

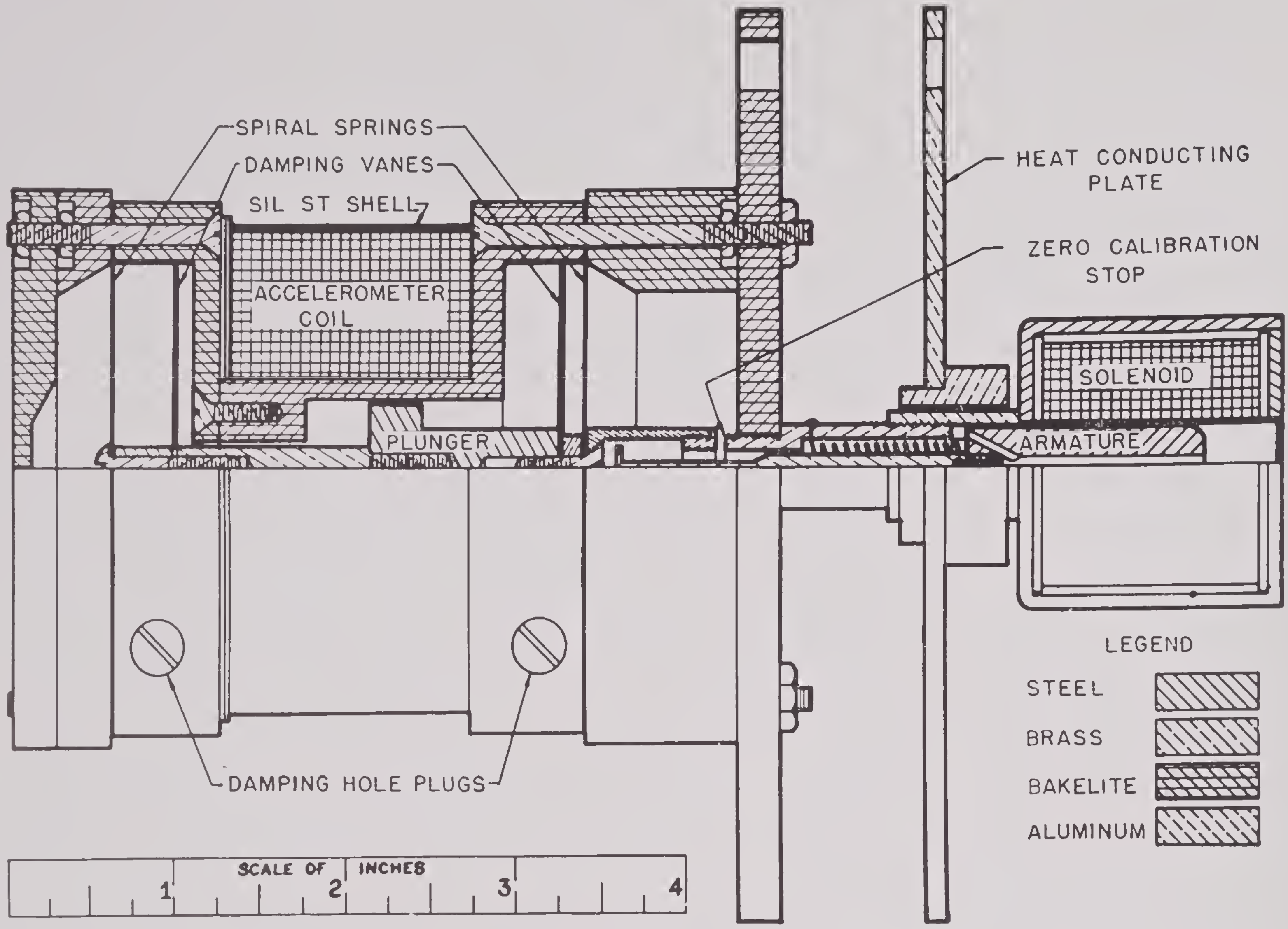

FIGURE 4. Assembly drawing of accelerometer.

with the time of a signal given when the bomb is released. It is necessary to have communication with the plane so that the equipment may be turned on and adjusted before the bomb is released. Figure 5 is a block diagram of the recording equipment.

The output of the Variac goes to the Hallicrafter receiver, the 180-v power supply, the 135-v power supply, and the charger. If the plane transmits a signal at the time the bomb is released, the National 1-10 release channel receives the signal and indicates the time of release by driving an oscillograph element in the photographic recorder. The National 1-10 time-pulse channel serves to calibrate the timing lines on the photographic tape so that the time of flight of the bomb may be accurately determined; it also allows the record to be correlated with other tests being made on the bomb. The Hallicrafter S-27 receives the signal transmitted by the retardation unit in the bomb. The recorder amplifier converts the audio output of the S-27 at about 850 c into a beat frequency of 25 to 125 c for retardation and into a direct current for impact. The synchronous timing-line motor is driven by the output of a tuning-fork amplifier.

The photographic recorder has six oscillograph elements having a natural frequency of 200 c and a sensitivity of about 2 mm per milliampere, mounted in pairs in double-element boxes; it has a seventh element having a natural frequency of about 44 c and a sensitivity of about 30 mm per milliampere, in a single-element box, for high sensitivity. The camera holds 3 31/32-in. seismograph recording paper and is equipped with a magazine and a collector each holding 200 lineal ft. A paper speed of 8 to 15 in. per second may be used.

Figure 6 shows a portion of a bomb-retardation record. The average beat frequency at certain intervals is determined from such a record by an appropriate method of differences. These beat frequencies together with the calibration constants of the unit and the zero-calibration correction permit plotting the retarda-

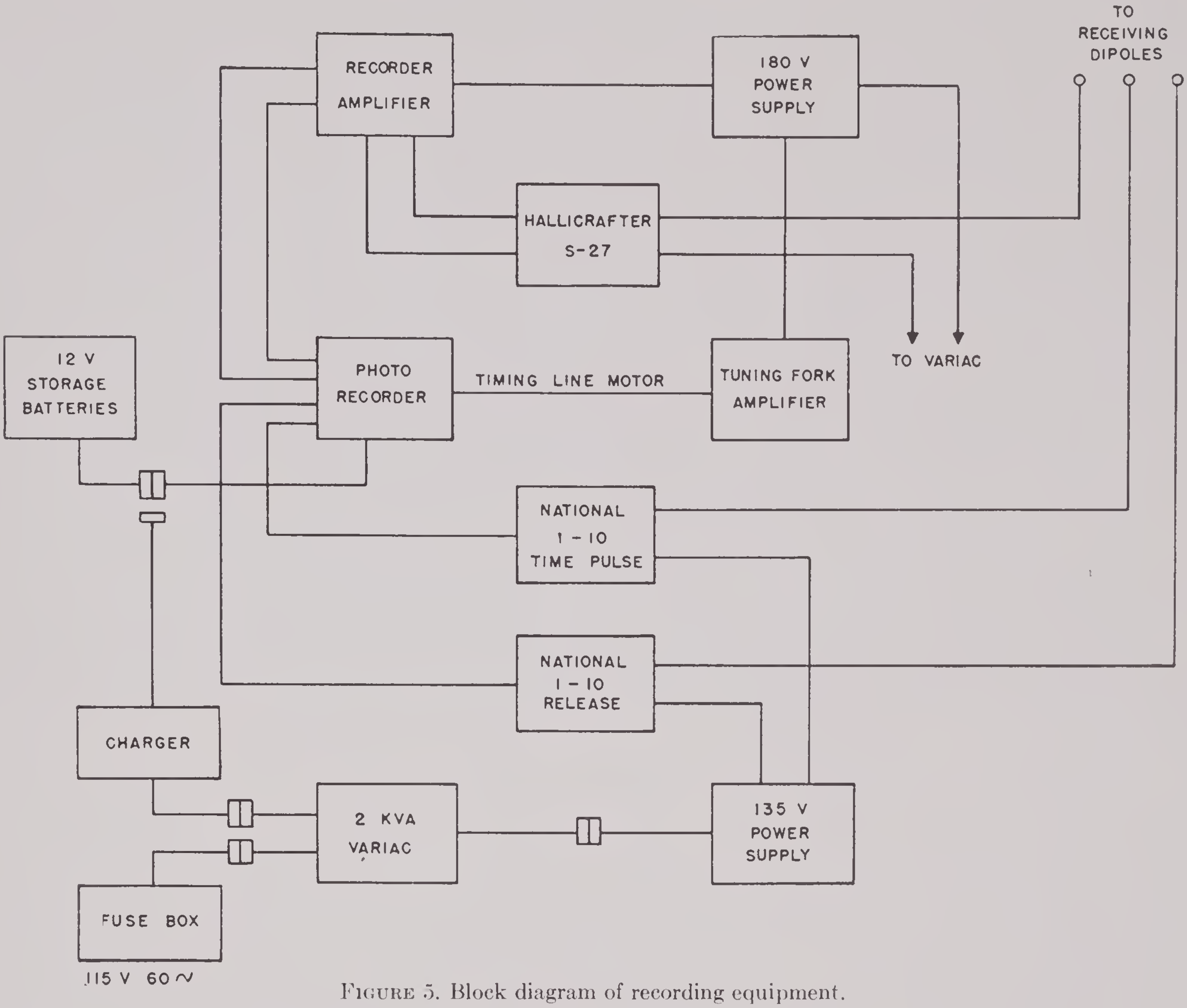

FIGURE 5. Block diagram of recording equipment.

tion as a function of the time, as is done in Figure 7.

The curves in Figure 7 are for two different tests. In plotting the curves the retardation of each unit was determined at nine evenly spaced points in each second and the curves were drawn through the plotted points. The smoother of the two curves is for an accelerometer near the center of mass; the more ragged curve is for a test in which the accelerometer was attached to the bomb plate about 42 in. from the center of mass, and shows the effect of centrifugal accelerations resulting from pitch and yaw superimposed on the retardation.

6.4.2 Seismographic Instrumentation and Technique

The seismographic tests showed that the ground characteristics of the new bombing field at Aberdeen are ideal for bomb-impact and distance measurements. The seismic wave generated by a 100-lb bomb dropped from 2,000 ft is sufficient to give a good "arrival" 500 ft from the impact point. The noise from the carrying plane registers on the detector either through the air or through the ground disturbance set up by the sound waves. Obviously bomb records must be above this noise level. On the basis of observed noise from the experimental plane the following table of minimum bomb size for good arrivals on a detector 500 ft from the impact was computed.

Height of plane	Minimum bomb size	Approximate nitrostarch equivalent
2,000 ft	100 lb	3 lb
5,000 ft	20 lb	1.5 lb

Although it is quite possible to measure bomb impacts under more adverse conditions by reading events one half or one cycle late and apply-

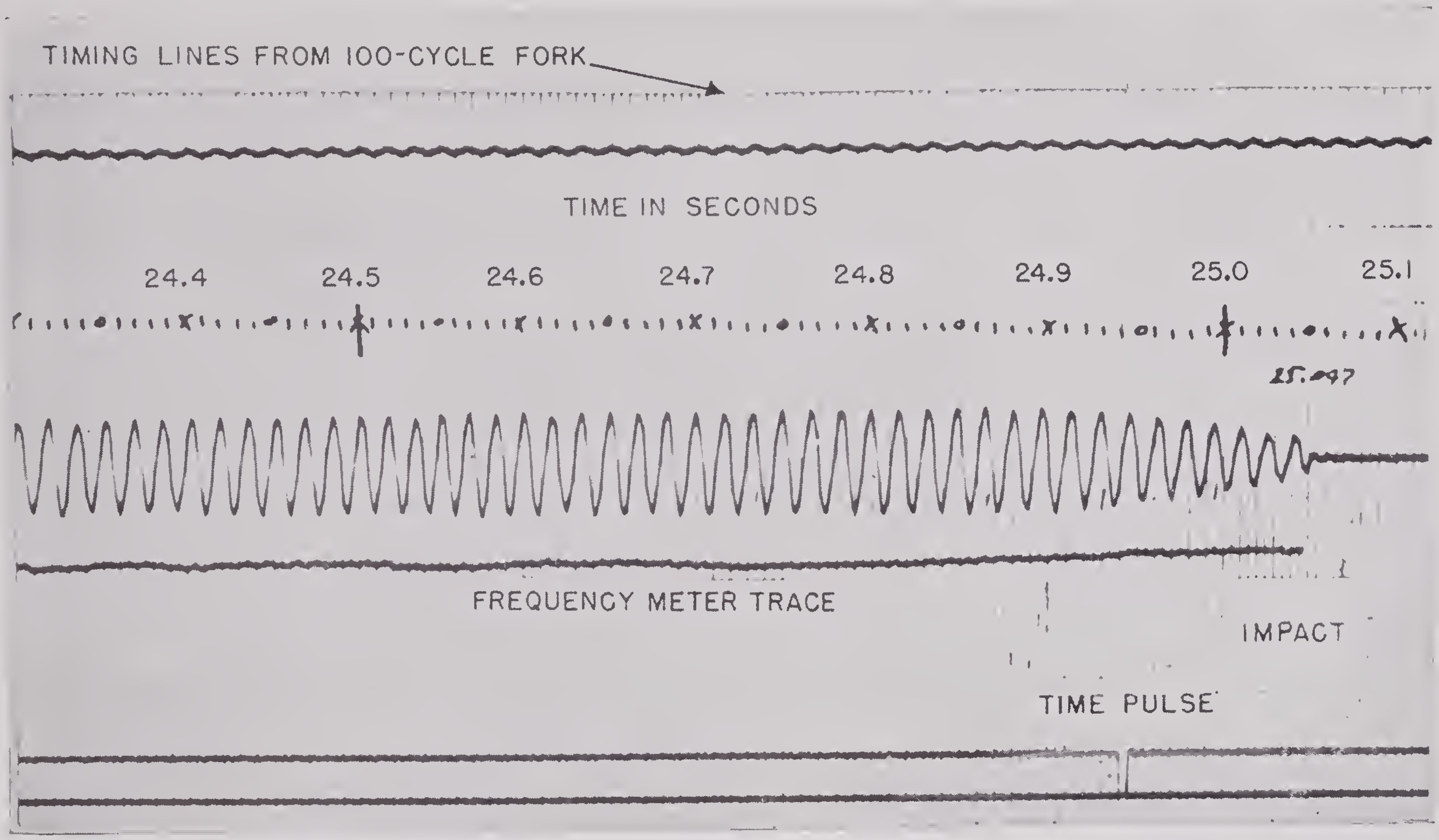

FIGURE 6. Portion of bomb-retardation record.

ing a uniform correction, the accuracy suffers considerably. An accuracy of 0.002 second in the determination of impact time may be obtained in this area by the firing of nitrostarch (or dynamite) charges at the points of impact, or by a seismic calibration of the area. There being no outstanding differences in the behaviors of seismic detectors with natural frequencies of 15 c and 30 c, it was recommended that from the standpoint of ruggedness 30-c detectors be used.

For the location of the point of impact, some sort of spatial arrangement, or "grid," of seismic detectors is necessary; and the arrival time of waves at not less than three detectors must be determined. The contractor's reports[5,8] give diagrams facilitating the calculation of impact locations for certain grid arrangements, and they discuss in some detail the degrees of accuracy which can be expected for different grid arrangements. In addition, they specify procedure for seismic reconnaissance (or evaluation) of a range-bombing site and for seismic calibration of a range-target area.

Tests were made in Chesapeake Bay to determine whether seismic measurements of bomb impacts on water could be made by means of vertical-component detectors buried on the bottom. It was doubtful whether sufficient accuracy could be obtained to allow the use of seismic methods for determining location and the instant of impact on the water. Although the tests were not conclusive in that they did not include all of the available methods of measuring seismic arrivals, it seems apparent that a bomb does not generate a steep seismic wave front upon impact but transmits its energy more gradually to water than to ground. This will probably prevent measurement of impacts on water from being made with the same degree of accuracy as those on land.

6.5 HISTORY

When work on this project was first started a number of methods of determining retardation were considered. There were four possible schemes.

1. To determine the change in pressure in a liquid under the retarding forces on the bomb.
2. To determine the change in resistance of a resistance strain gauge with a suitable mass attached to it.
3. To determine the change in inductance of

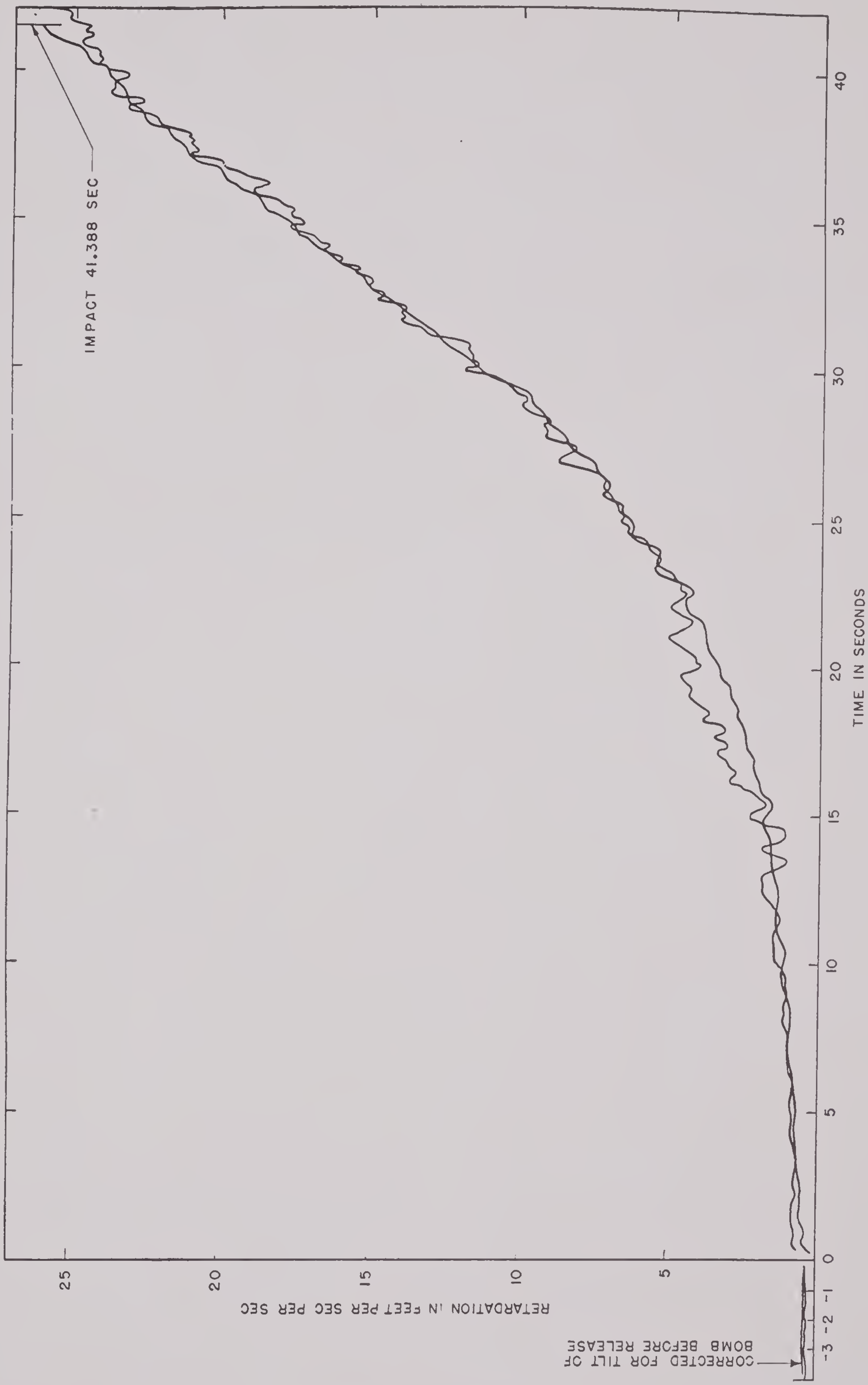

FIGURE 7. Plots of bomb retardations as functions of time.

a coil due to a change in the reluctance of the magnetic circuit occasioned by the retarding forces on the bomb.

4. To determine the change in capacitance of a condenser due to motion of its plates occasioned by the retardation forces on the bomb.

No experimental work was carried out on schemes (1) and (4). Some rough tests were made on (2), but (3) looked so much more promising from preliminary tests that it was the one actually developed.

From the beginning the development was straightforward, with modifications resulting from actual bomb tests conducted from time to time at the Aberdeen Proving Ground. For example, one such modification of the original plan was the inclusion of the solenoid arrangement for holding the plunger in a fixed position while a beat frequency was recorded just prior to release of the bomb. Before such an arrangement was adopted it was necessary to record the beat frequency when the bomb was in position in the plane and to determine the "effective retardation" associated with that beat frequency from the angle of inclination of the axis of the bomb.

Chapter 7

DEFLECTION-TIME MEASURING DEVICES[a]

By *F. L. Yost*[b]

7.1 INTRODUCTION

THE U. S. NAVY BUREAU OF SHIPS was conducting an extensive series of tests of damage from underwater explosions against simulated hull shapes and caissons, in order to evaluate the effectiveness of different types of structures in resisting explosive forces. Some of these tests were made on full-scale and others on reduced-scale models. Due to the cost of labor and materials in constructing caissons of the type used, it appeared to be essential that the utmost in useful information be derived from each test. The most useful measurements were those of deformations and deflections of various portions of a structure as functions of time plotted on the same axis.

Prior to the development recorded here, measurements of initial movements in such tests had been obtained from velocity meters and accelerometers, the remaining movements being measured by deflection-indicating devices such as "streak" cameras, plastic strain gauges and banks of contactor points. None of these devices had the desirable feature of providing, on a single continuous record and consequently on one time base, complete information as to the velocity and deflection (both positive and negative) of a given point on a test bulkhead.

The Bureau of Ships therefore requested that a project be set up by the National Defense Research Committee for the purpose of developing devices for the measurement of displacement as a function of time.

7.2 MILITARY REQUIREMENTS

It was requested that two types of device be developed: (1) one not involving mechanical attachment to the moving target, and (2) one involving attachment to the target, provided only that this type offered substantial simplification over the former.

The basic performance specifications were as follows.

1. The device was to record deflections of from 2 to 3 ft.

2. The device was to provide a good record of the path of a point on the structure as a function of time after impact, even if the point attained velocities of 300 or more feet per second.

3. Any device attached to the moving target was to withstand high initial accelerations (estimated to be possibly $2{,}000g$), although it need not record the values of the accelerations.

The most immediate need of the Bureau of Ships was for a device to use in connection with large-scale tests. In such tests the deflections encountered were of the order of 12 in. and the model was of such size that the attachment of a moving member to it did not detract appreciably from the accuracy of the measurements. Accordingly, the first type of unit developed was an *electromagnetic deflection unit* [EMU] which required the affixing of a member of the test object.

Sometimes the tests conducted by the Bureau of Ships are on as small a scale as $\frac{1}{16}$, that is, the gauge of the metal used is $\frac{1}{16}$ full-size and the charge is suitably reduced. For tests on such a small scale, the metal is so light that attaching a test device to it would affect the results. Accordingly, when the EMU was nearing completion the Bureau of Ships asked that the contractor devote his efforts to the other part of the original request, namely the development of a device not requiring attachments to the test object or requiring attachments with so little inertia as to have no appreciable influence on the results from a model of considerably reduced scale. The *optical deflection gauge* [ODG] resulted from this phase of the work.

The basic specifications for the ODG were as follows.

1. A minimum of apparatus was to be attached to the structure under consideration and its nature to be such as not to alter in any appreciable

[a] NS-197.

[b] Technical Aide, Division 17, NDRC.

way the deflection of the test structure itself.

2. The device was to record a deflection range of at least 15 in.

3. The deflection was to be recorded to an accuracy of ⅛ in. over the 15-in. range.

4. The device was to have stability and reliability of operation.

7.3 SUMMARY OF DEVELOPMENT

This project was conducted under contract with Faximile, Inc. The first apparatus developed[1] was the EMU. With this device the maximum error introduced by changes in magnetic environment during a test (which determined the overall accuracy) was less than 5 per cent. Both positive and negative bulkhead movements were recorded on a linear time base in units of 100 microseconds. The actual time at which the charge was set off could be indicated directly on the record. Bulkhead velocity and acceleration could be calculated from the deflection record. Deflections of several points on the bulkhead could be recorded on the same time base by using two or more units. The control and recording apparatus could be installed at locations as far as 900 ft from the caisson under test. Three units of this type were supplied to the Bureau of Ships.

The second device developed[2] was the ODG, which satisfactorily fulfilled the requirements imposed on its development. One unit of this type was supplied.

7.4 DESCRIPTION AND TECHNICAL INFORMATION

7.4.1 Electromagnetic Deflection Unit

The EMU[1] (in conjunction with an oscilloscope and recording camera) is an electronic device designed especially to measure the deflection and velocity of a test bulkhead during the time it is undergoing the effects of an explosive charge.

With the EMU, this is accomplished by measuring the coupling between two coils. One of them is mounted directly on the test bulkhead and is energized to produce a 10-kc electromagnetic field; the other is mounted opposite on the fixed bulkhead, or other stable mounting. It is aligned on the axis of the driver coil, and is used as a secondary coil in which a 10-kc voltage is induced. The induced voltage varies with the distance between the coils and its variation is used to measure that distance.

Movements of the test bulkhead are thus resolved into amplitude variations of a 10-kc signal across the pickup coil. This signal is amplified and applied directly to the deflection plates of an oscilloscope. The trace of the oscilloscope is photographed on a strip of 35-mm film mounted on a revolving drum the peripheral speed of which is such that measureable definition is given to the 10-kc signal.

In recording the signal, the oscillogram is limited to an amplitude of 20 mm peak to peak. Due to the coarse grain of the highly sensitive film used, this limited amplitude of recording would result in poor definition of small signal variations, thus contributing to low sensitivity of the entire system. For example, in recording a 12-in. bulkhead deflection as a 0- to 20-mm amplitude on the film, it would be impossible to define on the record amplitudes corresponding to less than ¼-in. deflection. However, by dividing the 12-in. deflection into three equal ranges and consecutively recording them as 0- to 20-mm amplitudes, almost three times the original definition is obtained. The shift from one range to the next is automatic, and accomplished electronically.

The schematic arrangement for a test is shown in Figure 1. The electric circuit diagram for the EMU is given as Figure 12 in the instruction manual which accompanies the original report[1] of this device. The oscillator-amplifier section supplies a high-level source of stabilized 10-kc power to the driver coil which is cable-connected to its output.

The driver coil is a center-tapped 2-mh inductance wound on a 3-in. form and requires a capacity of about 0.12 μf to resonate at 10 kc. The pickup coil is a 1-mh center-tapped inductance wound on a 12-in. diameter form. In a test, the two coils are rigidly mounted on bulkheads so that the driver and pickup coils are on a common axis and initially at a predetermined distance from each other.

Measurement of bulkhead deflection with the EMU consists basically of recording amplitude

variation of the 10-kc signal induced in the pickup coil as the coupling distance between the two coils varies. This record is interpreted by comparing it against a calibration curve plotted from values of amplitude for unit steps of the

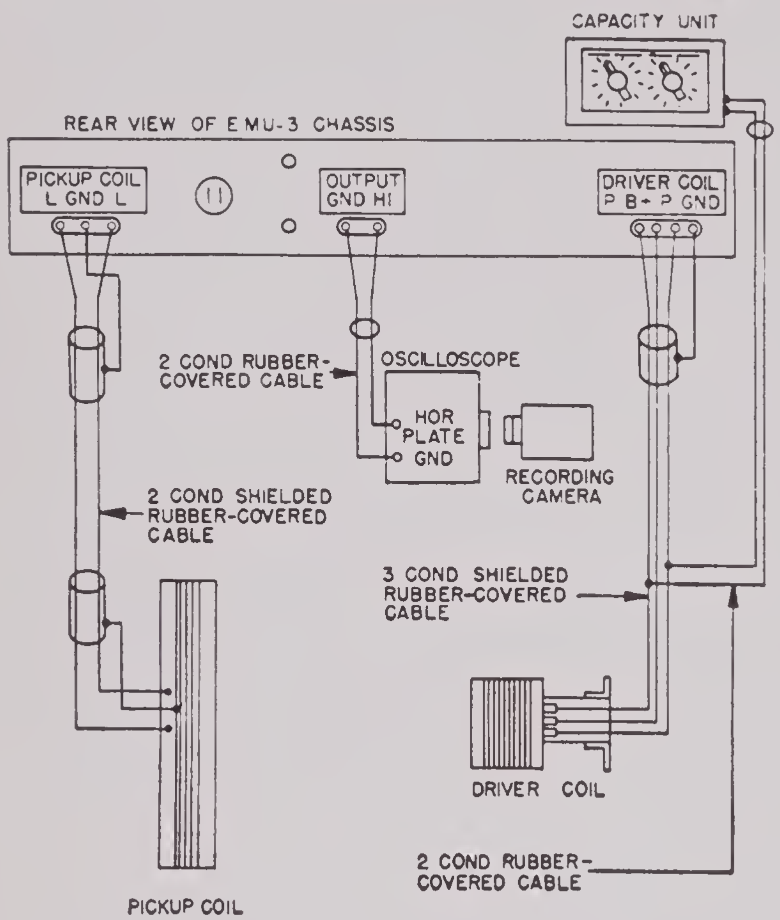

FIGURE 1. Schematic diagram of arrangement for test.

coupling distance between coils. Curves of coupling characteristics made within test caissons were found to be closely logarithmic. These characteristics are subject to variations due to magnetic environment but, for the purpose of illustration, a logarithmic-coupling curve can be assumed as indicated in Figure 2.

In recording amplitude variations of the 10-kc signal on film for any deflection range, it is necessary that the gain control of the amplifier in use be adjusted so that the maximum voltage induced in the pickup coil (corresponding to the maximum deflection of any range) is resolved into a 3-in. oscilloscope trace that may be photographed within the lateral limits of the 35-mm film.

In attempting to record a deflection of 18 in., from an initial spacing between coils of 36 in., the ratio of maximum to minimum voltage is very small at the beginning of the range and increases sharply toward the end. Recording a deflection in this manner would result in a very poor definition on the film of variations within the first half of the range.

By making use of a separate amplifier channel for each 6-in. step of the assumed 18 in.—each amplifier incorporating an individual gain control which can be adjusted to keep the oscilloscope trace within the limits previously mentioned—it becomes possible to secure almost three times the sensitivity and definition obtainable with a single-channel amplifier. Figure 3 shows an oscillogram obtained with such an arrangement. Note that the 10-kc signal is sufficiently defined in the oscillogram that it can be used for the time basis.

The three channels mentioned above are fed into a common output system so that only one oscilloscope is necessary to make the complete record. A trigger circuit consisting of two tetrode thyratrons and a dual triode is employed in order to switch each channel into operation only for the duration of the 6-in. step for which its gain control has been adjusted. During actual operation, the three amplifier channels are connected in parallel and the initial condition is such that only the first channel is in operation, while the remaining two are biased to cutoff. The rising output voltage of the entire amplifier system is used to trigger a thyratron tube at the completion of the first 6-in. step which, in turn, biases the first channel to cutoff and removes the

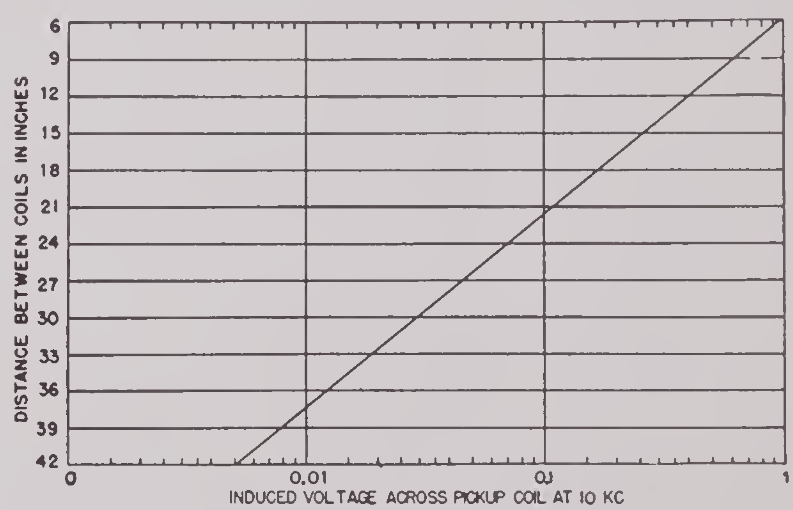

FIGURE 2. Relation between voltage induced in pickup coil and distance between pickup and driver coils.

high bias from the second channel, causing it to become conductive. The gain control of the second channel is adjusted for the second 6-in. step, at the completion of which the output voltage is again used to "fire" a second thyratron biasing the second channel to cutoff and causing the

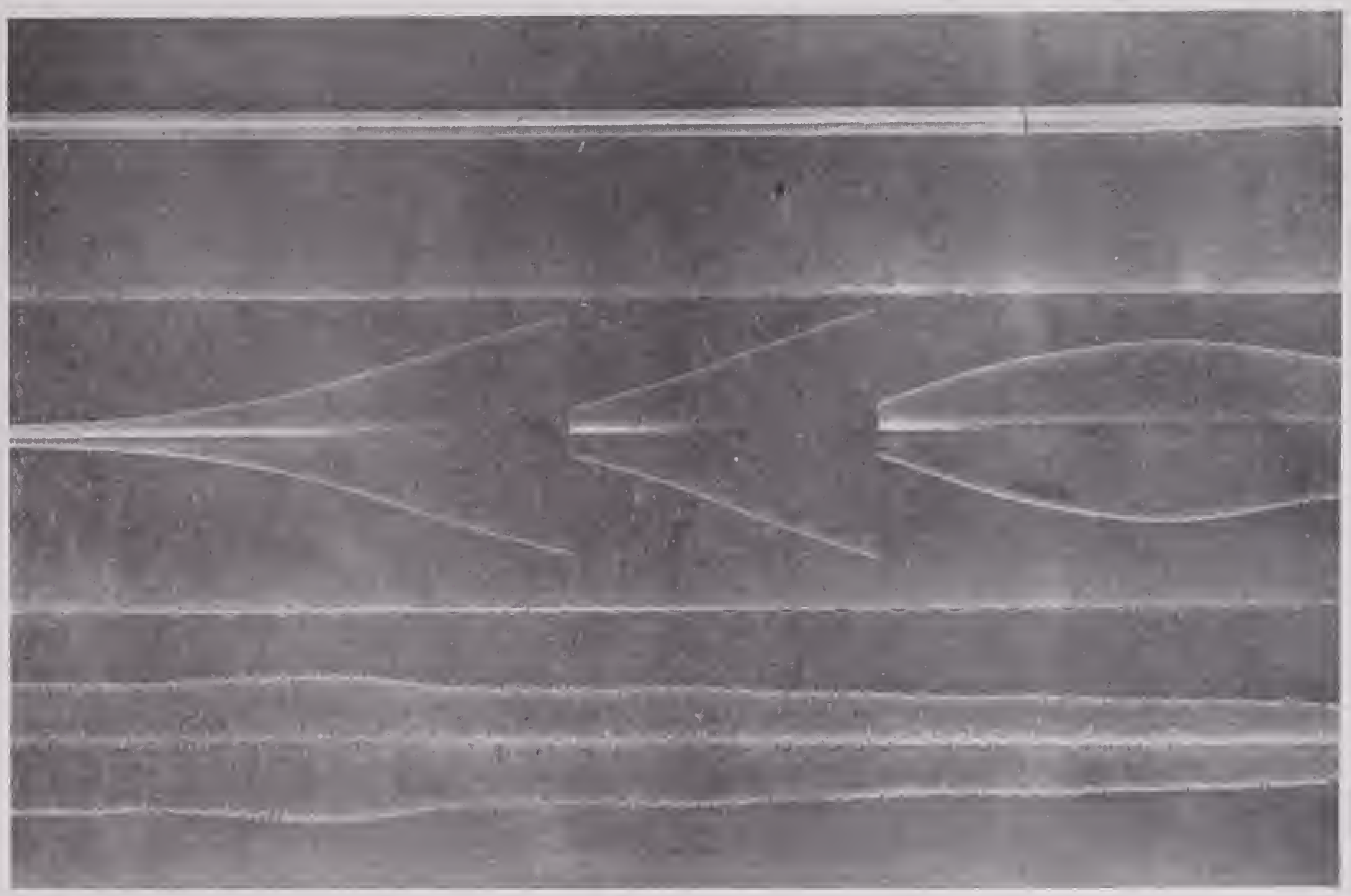

FIGURE 3. Typical EMU-3 deflection record.

third channel to become conductive. In addition to all this, a threshold limiter is incorporated within the amplifier which can be adjusted to pass only those voltages above the initial level (i.e., no signal is recorded when the coils are at their initial separation). Also, the first and second and the second and third ranges are arranged to overlap slightly so that both positive and negative bulkhead readings can be recorded during an explosion.

In connection with recording the comparatively large deflections of about 36 in., the initial movements of the bulkhead demand the greatest interest and require that the first two ranges of the EMU be adjusted for high sensitivity. This may be accomplished only by decreasing these ranges, with the result that the third range is also necessarily decreased, making it impossible to record the entire deflection over the three ranges. However, by incorporating an additional thyratron tube the function of which is to reduce the threshold value of the limiter stage for the duration of the third range, it becomes possible to record greater deflection distances within this range, since the voltage range of the third channel is increased. The unit which does this is called the EMU-3B *range expander unit* [REU].

7.4.2 Optical Deflection Gauge

After the development of the EMU and the REU, it was deemed desirable, for reasons already mentioned, that the ODG[2] be developed. The operation of the device is based entirely upon optical principles, necessitating the attachment of a minimum of apparatus to the moving object under consideration.

The ODG consists of two separate pieces, the *light unit* [LU] and the *power unit* [PU]. In a test arrangement, the LU and PU are supplemented, as shown in Figure 4, by a voltage regulator, a recording amplifier, and a recording oscilloscope.

The LU consists of two coaxial optical systems, one for transmitting light and the other for receiving it. Essentially, the device measures the distance betwen the LU and a reflecting surface on the optical axis by measuring the mag-

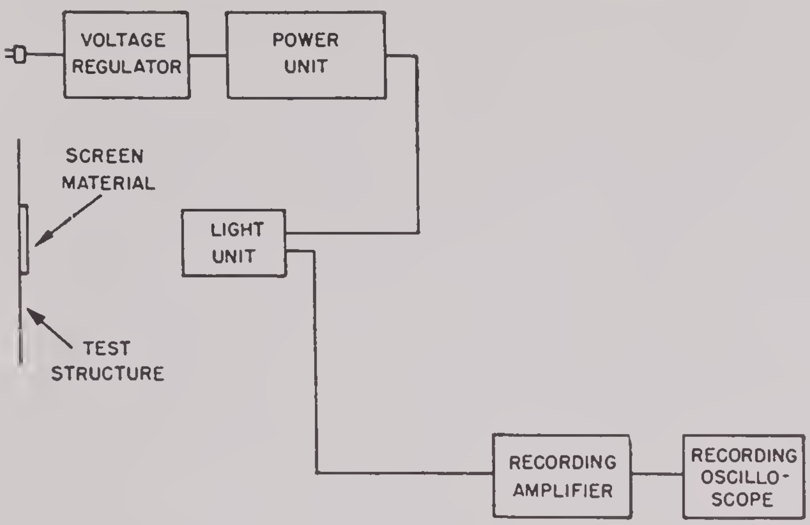

FIGURE 4. Arrangement of optical deflection gauge for testing structure.

nitude of the reflected light received by the unit for a fixed magnitude of transmitted light. The idea involved is that light is reflected diffusely from the reflecting surface and that therefore the amount of light received back by the unit the 10-kc output of the phototube is a measure of the distance to the reflecting surface.

It was originally hoped that the amplifier for the EMU could be used with the ODG, but it was later found that this might not always be possible. During tests transient signals are frequently generated in the ODG by light flashes of strobotrons. Each flash interferes with about three or four cycles of carrier frequency because of poor low-frequency response of the EMU amplifier. The representatives of the Navy were aware of the limitations of the EMU amplifier when used with the ODG, but they did not request NDRC to design a different amplifier. The development of a suitable amplifier was left to naval personnel.

The arrangement of the LU is shown in Figure 5; and the circuit diagrams for the PU and LU are shown in Figure 6. The light source is an R-1130 facsimile lamp, the current of which

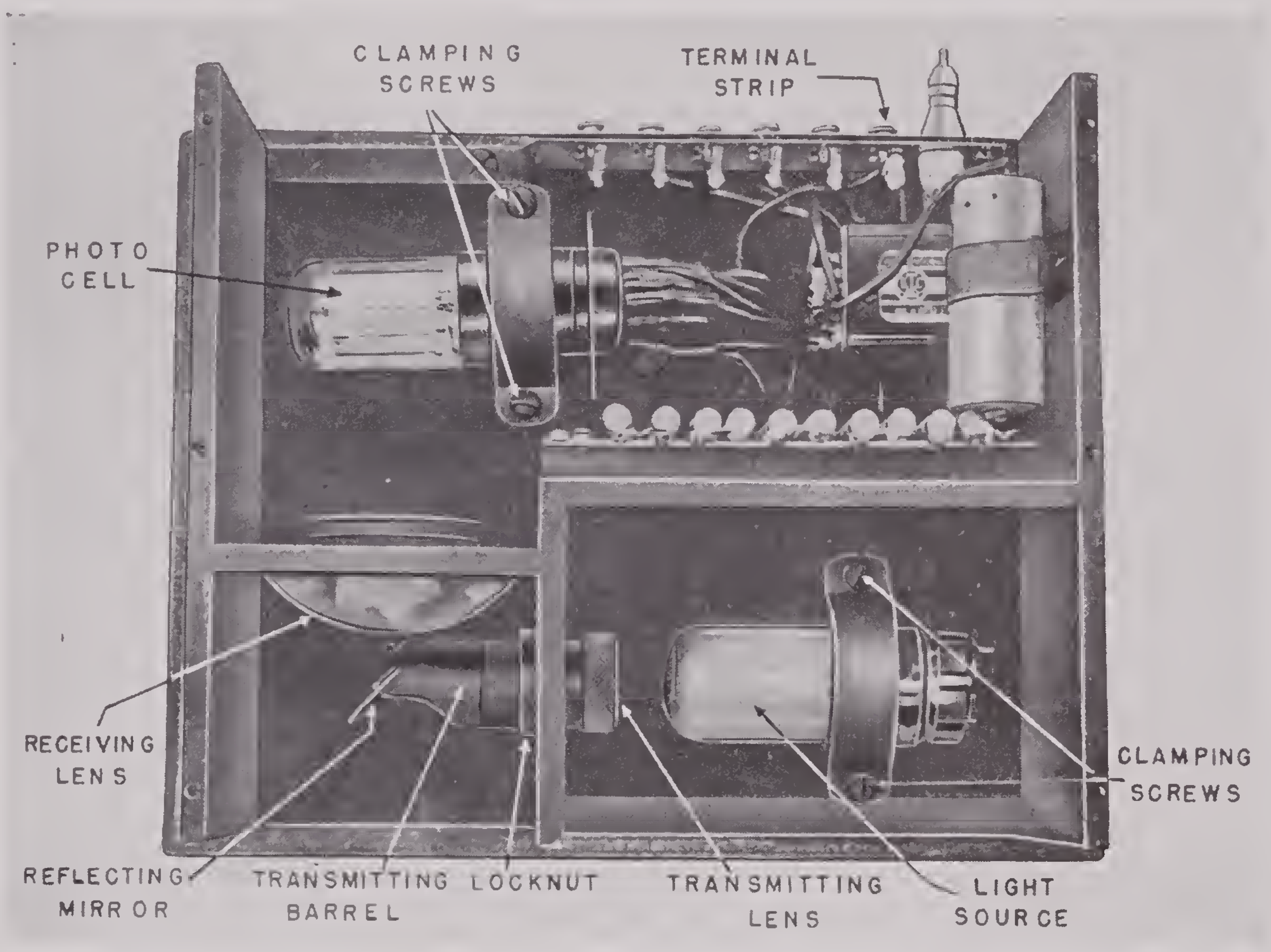

FIGURE 5. Top view of light unit.

through a fixed aperature varies with the distance of the reflecting surface from the aperture.

The light source in the LU is modulated at 10 kc. The received reflected light is focused upon a phototube; and the relative amplitude of is modulated at 10 kc. The light falls upon the transmitting lens, which is mounted in the end of the transmitting barrel. The latter extends from the source compartment into the lens-mirror compartment, and terminates in a small mir-

ror set at an angle of 45 degrees with the axis of the barrel. The arrangement is such that the light collected by the transmitting lens is rendered very nearly parallel and is conducted along the length of the barrel, at the end of which it is reflected out of the LU by the mirror. The extension of the transmitting barrel into the lens-mirror compartment is such that the light leaves the LU along the axis of the receiving lens, which is mounted directly behind the barrel in the wall between the lens-mirror compartment and the photoelectric cell compartment. The returning light, reflected from a distant object, is collected by the receiving lens and is focused upon the 931-A photoelectric cell.

Power is furnished to the LU by the PU. Connections between the two are made by means of a 5-conductor cable not over 20 ft in length. Terminals numbered 1 through 5 in the PU are connected respectively to terminals numbered 1 through 5 in the LU. Terminals 6 and 7 of the PU are for use in adjustment of the percentage of modulation of the light source.

As indicated in Figure 5, a 2- or 3-in. circle of reflecting material is attached to the point of maximum deflection for a test. The reflecting material is a piece of glass-beaded movie screen because its reflection is relatively insensitive to the angle of incidence. (The percentage of reflected light from this material was constant for angles of incidence up to 30 degrees from the normal, and fell off slightly over 4 per cent at 45 degrees.)

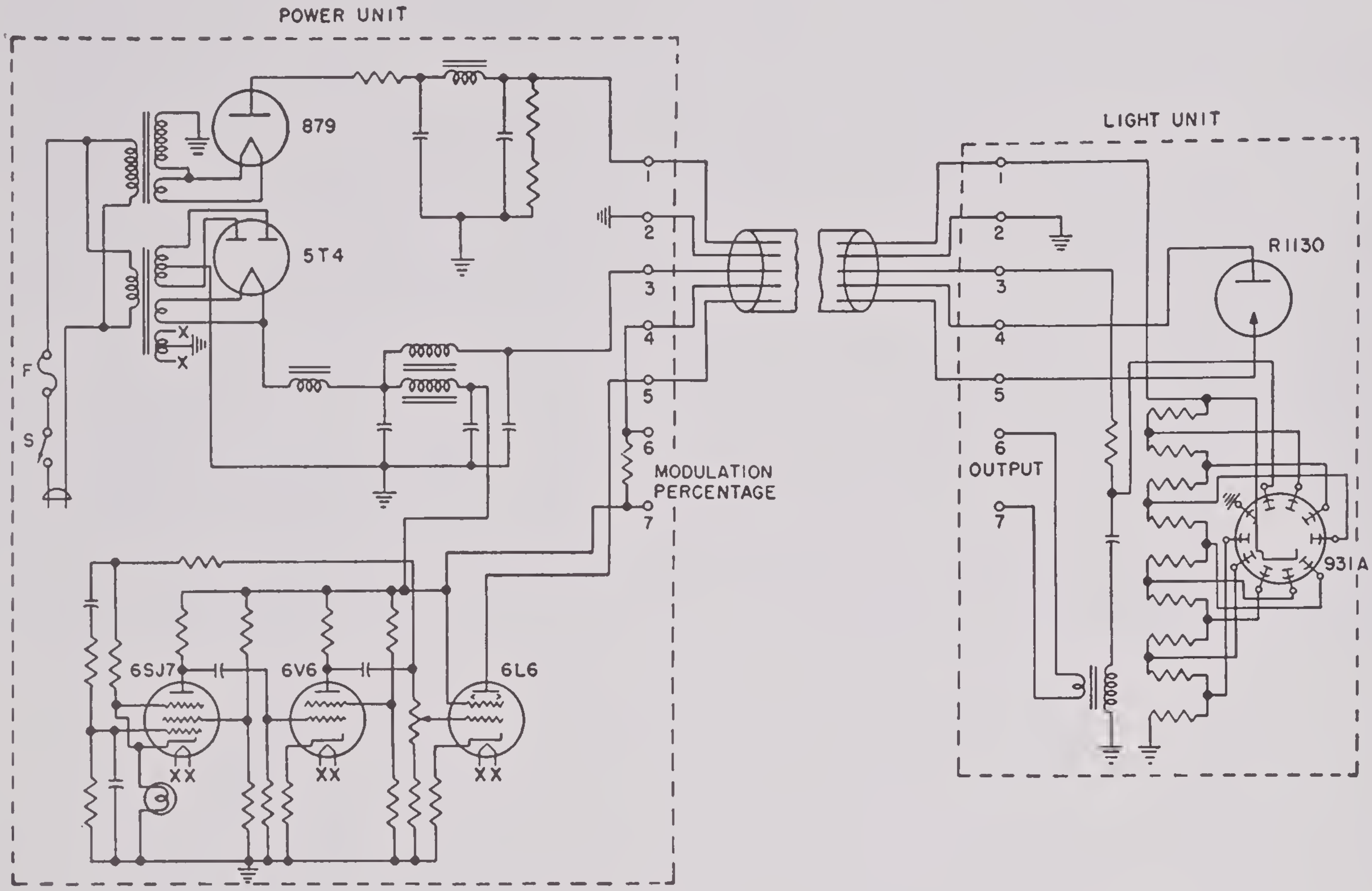

Figure 6. Circuit diagram for power unit and light unit.

The LU must be fastened to a rigid support with an anti-shock mounting; it must be arranged so that the light beam from the unit will strike the center of the screen, and so that the direction of travel of the screen during the course of the explosion will be along the axis of the light beam. It should be mounted as close to the test bulkhead as possible, allowing a reasonable margin of safety beyond the expected deflection distance of the test.

The PU may be placed in a convenient location not to exceed about 20 ft from the LU. The voltage regulator must be connected in the line at the PU so as to control only the voltage supplied to this unit. The output of the LU is at

50-ohms impedance and may be cabled over relatively large distances, which permits the recording amplifier, oscilloscope, and camera to be set up at any convenient point.

The calibration of the LU is dependent only upon the constants of the optical system; i.e., the apertures and focal distances involved. As a result, the relative output of the unit for various distances should remain constant as long as these factors are not disturbed. Figure 7 shows

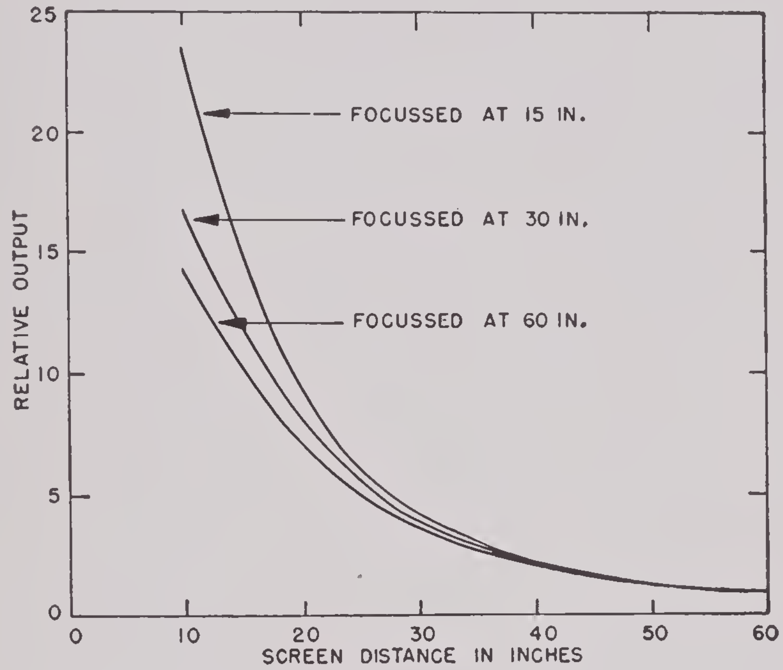

Figure 7. Effect of focusing distance on relative response.

the relative output for the system when focused for the screen material at different initial distances. In obtaining each of these curves, the optical adjustments were made by setting the reflecting screen at a given distance and focusing the optical system for maximum output at that screen distance.

During calibration and during the time an actual test is in progress, stray light falling upon the screen material must be kept to a minimum, as the ultrasensitive 931-A phototube is easily overloaded. The presence of any appreciable stray light will render the calibration and test worthless.

7.5 HISTORY

When this project was first set up, a number of possible ways of measuring the bulkhead deflections was considered.[1] Of those which were not subject to serious difficulties, the electromagnetic method seemed the most direct. The development of the EMU was therefore undertaken. The final model was the result of a number of experimental models used in actual tests and described in the original report.[1]

When the development of a less bulky unit for small-scale tests was undertaken, quite a number of possible types were considered;[2] and it was decided that the ODG was the most promising. The major problems in connection with ODG were: (1) the development of a projection system providing a nearly parallel beam of light from 1 to 2 in. in diameter; (2) the development of a method of modulating the light source at a high audio frequency; and (3) the development of a photocell-pickup amplifier. These problems were susceptible to fairly straightforward solution; and the final unit resulted after some experimentation with an intermediate model.

Chapter 8

MEASUREMENT OF WALL THICKNESSES OF HOLLOW STEEL PROPELLER BLADES [a]

By *F. L. Yost* [b]

8.1 MILITARY REQUIREMENTS

The National Defense Research Committee was asked to develop a nondestructive method of measuring the wall thicknesses of hollow steel propeller blades. One of the reasons for this request was that it was desired to test a large stock of blades which were suspected of having weakened areas because of grinding.

The making of such measurements presents a number of problems. The size and shape of the blades introduce difficulty. In order to be of value the readings must be accurate to ±3 mils for a dimension which may vary from 40 to 300 mils. And, finally, the method devised must be simple and rapid. The requirement was, therefore, to develop a nondestructive, simple, rapid, easily managed method for measuring the wall thicknesses of propeller blades at various points to within an accuracy of 3 mils.

8.2 SUMMARY OF DEVELOPMENT

An instrument known as a *penetron* had been developed by the Texas Company for measuring the wall thickness of pipe. The principle involved was that a gamma-ray source and a gamma-ray counter was so situated outside the pipe that the wall of the pipe reflected and scattered to the counter gamma rays from the source. It was first hoped that this method, with minor modifications, would meet the requirement. It soon appeared, however, that reflection from the second wall of the propeller would introduce difficulties.

It was then decided to place the source *inside* the blade and to measure gamma-ray transmission to the counter *outside* the blade. This technique presented two major problems: (1) holding the source exactly opposite to and on the axis of the counter for all points which might be measured, and (2) selecting a radioactive source which would give the required accuracy of measurement.

The Texas Company solved the first problem by the construction of a pantograph which controlled the positions and attitudes of the source and counter. At the suggestion of Section 17.1, personnel engaged in nuclear research at MIT and at Ohio State College were called upon by The Texas Company for advice and assistance.

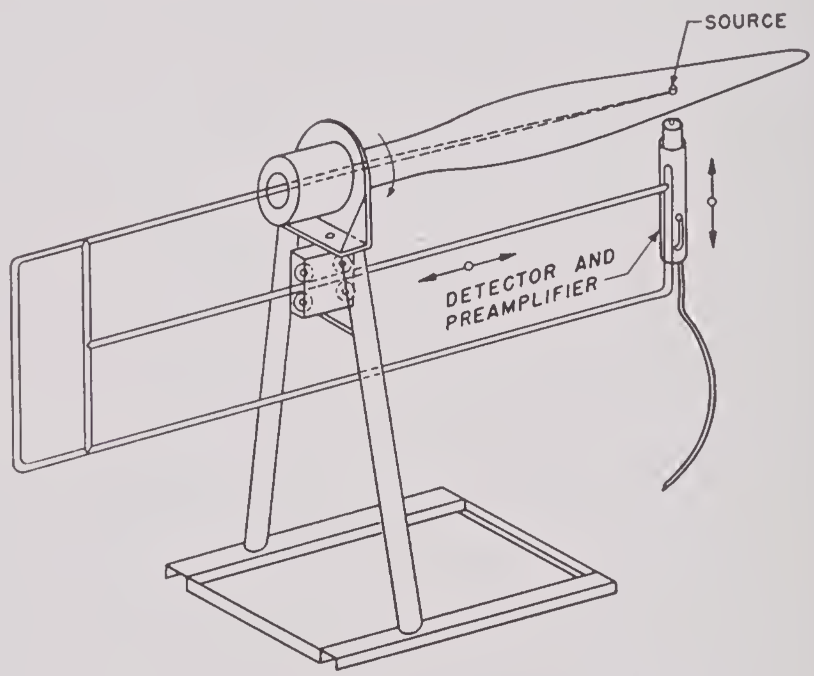

Figure 1. General arrangement of apparatus for wall-thickness determination.

In the measuring device as finally developed, a concentrated source of radioactive selenium (obtained by bombarding metallic arsenic with deuterons in a cyclotron) is pressed against the inner surface of the propeller wall. By means of the pantograph a Geiger-Mueller gamma-ray counter is pressed against the outer surface of the wall, directly opposite the source. The wall thickness between them can be determined from the length of time required to count a specified number of gamma rays.

The equipment was installed at the Propeller Division of the Engineering Laboratory, of

[a] AC-79.
[b] Technical Aide, Division 17, NDRC.

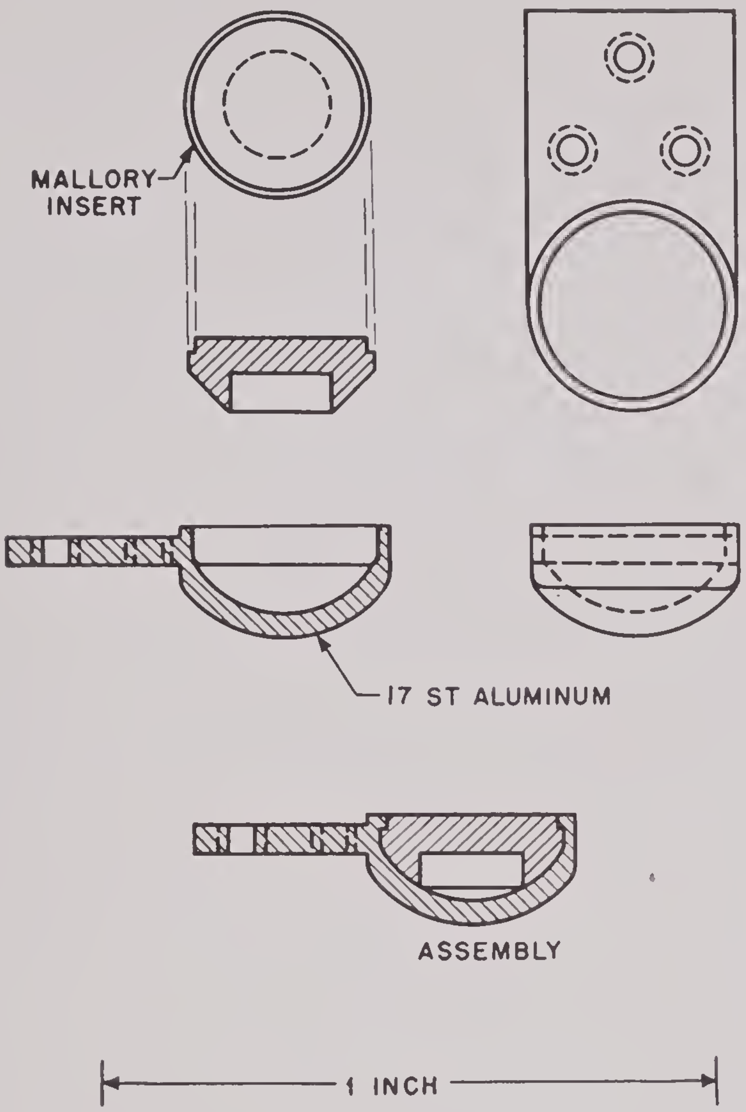

FIGURE 2. Radioactive-source holder.

Wright Field, Dayton, Ohio. Extensive tests as to its stability and reproducibility proved the instrument to be satisfactory. As a final test approximately 100 locations were measured on a standard propeller blade. Holes were then drilled at the stations measured and the wall thicknesses were checked with an Ames mechanical indicator. It was assumed that the indicator was correct, although experience showed that measurements at different points on the periphery of the same hole varied up to 10 mils. The gamma-ray instrument yielded values which were well within the specified accuracy requirements of ±3 mils. (Some of the measurements did have a much larger error, but they were all close to the shank at points where the pantograph had to be tilted appreciably. At such locations the source is shifted sufficiently from true alignment on the axis of the detector that errors are to be expected.) In general, the device completely satisfies the requirements.

In these tests it was found desirable to have the instrument warm up overnight. It required about 8 hours to measure 100 stations, or about 5 minutes per station. Two to three minutes were required for two readings at each station (actual reading time is about one minute) and the rest of the time at a station was required for adjustment of the blade and pantograph. It was estimated that operation time could possibly be cut 50 per cent by improvements in setting-up technique and by the use of a stronger source.

8.3 DESCRIPTION AND TECHNICAL INFORMATION

The general arrangement of the instrument is shown in Figure 1. There is a holder which supports the blade at its shank in a horizontal position and permits rotation of the blade about its longitudinal axis. Attached to the same framework is a two-arm pantograph. One arm supports the radioactive source on the inside of the blade, the other, the detector on the outside of the blade. The pantograph can be moved along the length of the blade and can also be rotated in a horizontal plane. Such motion supplemented by rotation of the blade permits reaching every point inside the blade and keeping the detector axis perpendicular to the wall.

During its passage through the wall from source to detector, the gamma-ray beam experiences a reduction in intensity due to absorption. The intensity of the beam at the detector therefore decreases with increasing wall thickness. It was decided to have the source and detector pressed against the wall surfaces because in such an arrangement an increase in wall thickness results in a reduction of detected intensity for two reasons: (1) the absorption is greater; (2) the detector is farther from the source, thus reducing the solid angle subtended at the source by the orifice of the detector. Furthermore, it was much easier to separate the source and detector

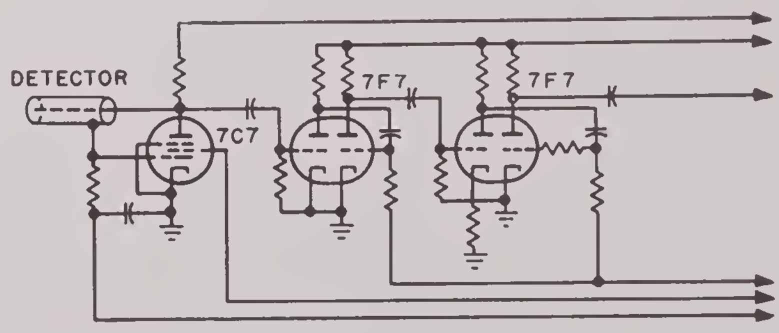

FIGURE 3. Detector and preamplifier circuit.

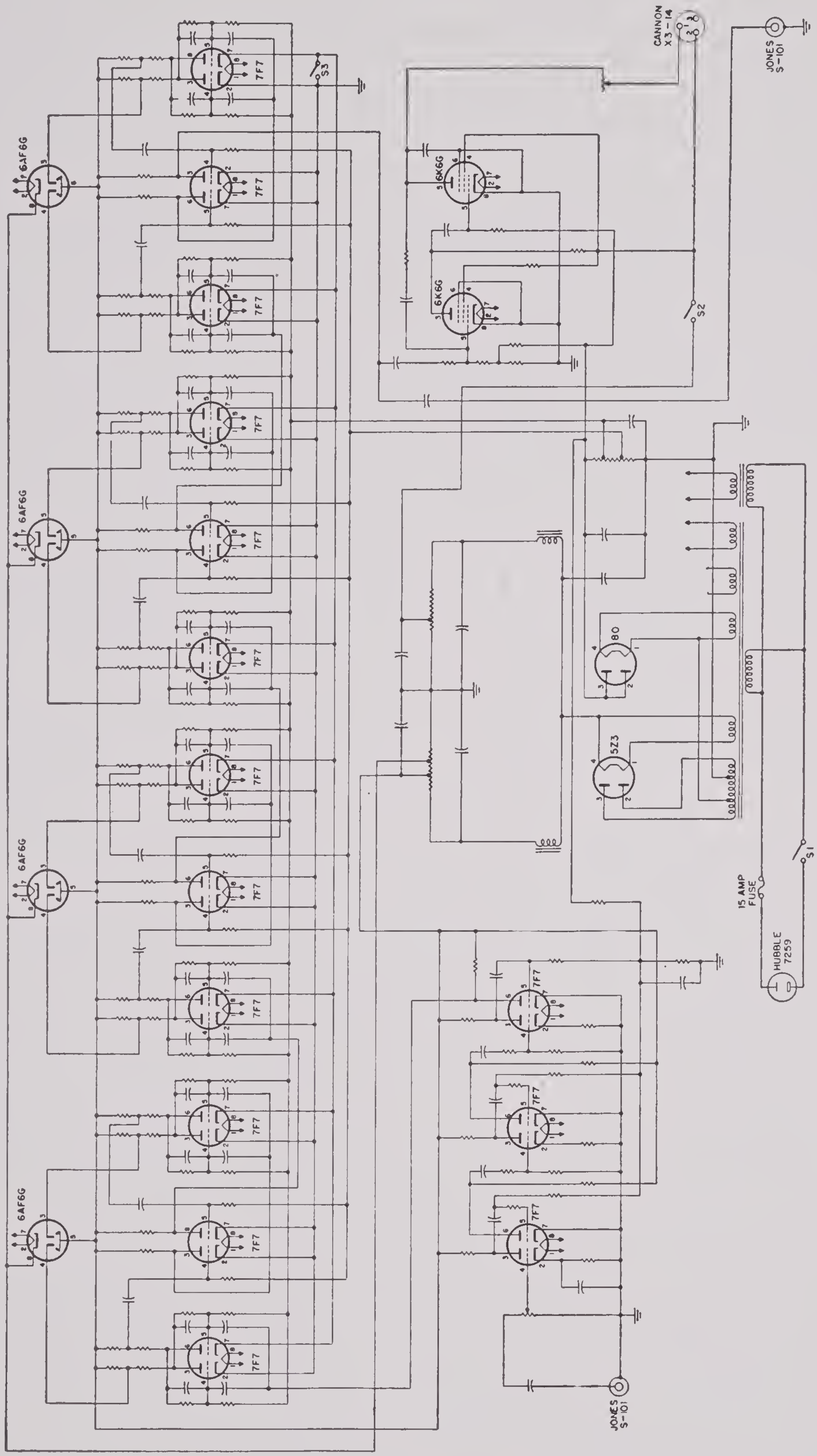

FIGURE 4. Amplifier and scale-of-256 counter circuit.

by the thickness of the wall than to hold them at a constant separation.

It is desirable to have as large a change of intensity as possible result from insertion of a given thickness of steel between the source and the detector. The lower the energy of the gamma rays, the higher is the absorption coefficient and hence, the greater the change. However, most substances with low-energy gamma rays have rather short lifetimes and are accordingly unsuitable. Selenium, with a half-life of approximately 180 days, seemed to be a suitable source material.

The instrument was finally equipped with such a source in the form of H_2SeO_4 dissolved in nitric acid. The solution was evaporated to a dry powder and placed in a source holder shown in Figure 2. The holder was made of "Mallory 1000," an alloy containing over 99 per cent tungsten. The walls were made sufficiently thick so that gamma rays not emitted toward the detector are absorbed to a high degree (in order to reduce the scattering effect of neighboring parts of the wall and of the back wall of the propeller). The radioactive powder is placed in the opening which is then filled with molten paraffin, which prevents any dislocation, and a thin aluminum cover is added. The source is supported by a thin sheet of stainless steel which is sufficiently flexible so that the source secures a positive contact between it and the inside of the blade.

The detector is a Geiger-Mueller counter tube of conventional design. Its current pulses are increased by a preamplifier, the electric circuit of which is shown in Figure 3. It involves a Neher quench circuit and two stages of pulse amplification. The detector and preamplifier are mounted in a shielded container which is connected by a multi-conductor cable to the rest of the circuit and the power-supply unit. The latter connects through a commercial voltage regulator to a 110-volt a-c line and supplies the necessary voltage to the preamplifier.

Figure 4 shows a circuit in which pulses from the preamplifier are further amplified, equalized, and fed into a counter circuit with a scale of 256 pulses per division. This arrangement allows the counting of every pulse, but the indicator need not operate so fast. Pulses from this counter circuit are fed into an electromechanical counter, the circuit of which is shown in Figure 5. The mechanical counter makes one revolution for 100 impulses. A contact is made by which an automatic electric timer is started at the zero position of the counter; and it is stopped after the counter has made three full revolutions. The timer therefore gives the time for counting 300×256 or 76,800 pulses.

Due to the nature of radioactive decay any measurement of intensities has a certain statistical error. This error decreases with an increase in the number of observed impulses. For the figure given above the average statistical error is 0.36 per cent.

Originally the Geiger-Mueller counter was not shielded against extraneous gamma rays, being open in all directions. It was soon found that with such an arrangement neighboring parts of the wall and the back side of the propeller blade influenced the reading. A lead plate of ¼-in. thickness was, therefore, placed inside the aluminum housing between its end plate and that of the counter. This plate has a hole at its center

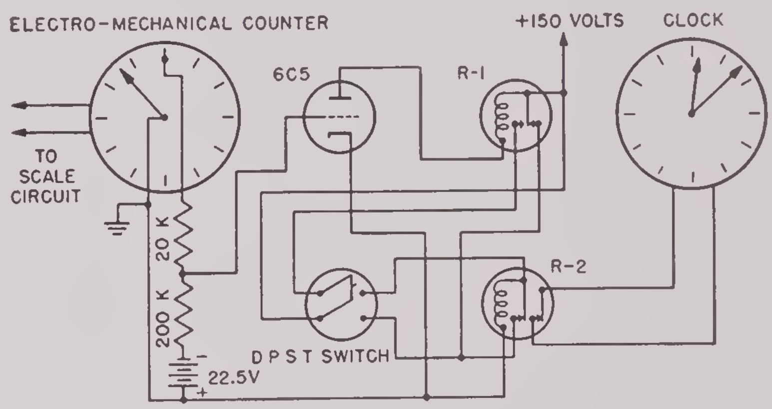

FIGURE 5. Counting mechanism.

R-1. Sigma relay micro switch, 2,000 ohms resistance; closes at 1.5 ma.

R-2. Leach relay, 10,000 ohms resistance, Type 1054, coil No. 361; closes at 80 volts on coil.

Electromechanical counter. Manufactured by Cyclotron Specialties Company:

Two indicators: (1) 0–10 minutes for one revolution.
(2) 0–0.10 minutes for one revolution.

Operation on 110 volts 60 cycles per second; electromagnetic controlled clutch starts and stops indicators; motor runs continuously.

Accuracy of system. ± 0.01 second for starting and stopping operation.

Operation: (1) With DPST switch in *closed* position, counter contact closed "locks" R-2, closing circuit to timing clock, starts clock. (2) With DPST switch in "open" position, counter contact closed "locks out" R-2, opening circuit to timing clock, stops clock.

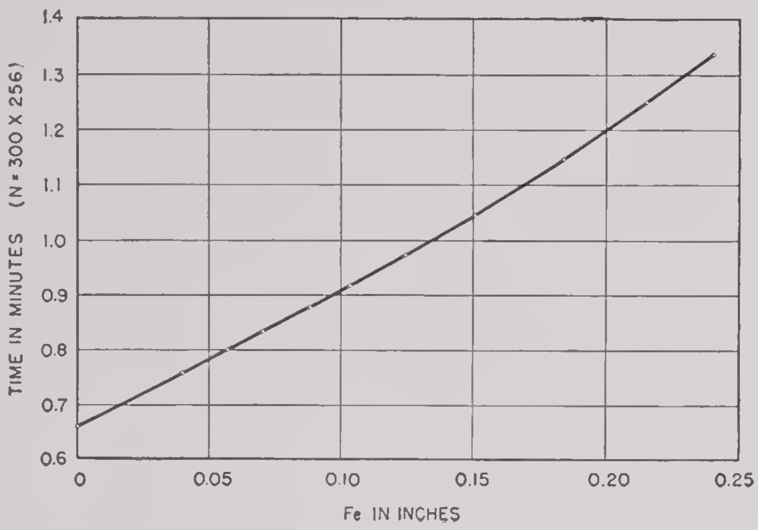

FIGURE 6. Calibration curve for shield with ¾-inch hole.

that is coaxial with the counter. After holes of various sizes had been tested, a diameter of ¾ in. was chosen. Figure 6 shows the calibration curve for this hole. The thickness of the sheet interposed between source and detector is plotted as abscissa and the time in minutes to count 76,800 pulses is plotted as ordinate. It was experimentally determined that the ¾-in. hole averaged the blade thickness over an area of 0.4 sq in.

One disadvantage of the selenium source is that after a period of 180 days the intensity of the gamma-ray beam has decreased to half of its original value. For accurate measurements the decrease in primary intensity must be taken into account. Practically, it turns out that the decrease per 24 hours corresponds to the absorption which is caused by a 2-mil thickness of steel. If a calibration curve as shown in Figure 6 is used, each day an additional 2 mils must be subtracted from the measured thickness. If the age of the source is unknown, a new calibration curve can easily be determined.

Chapter 9

DEVELOPMENT AND APPLICATIONS OF ELECTRONIC COUNTER CIRCUITS

By *George E. Beggs, Jr.*[a] and *F. L. Yost*[b]

9.1 INTRODUCTION

An electronic counter is an instrument which measures and records the number of electric pulses it receives from a suitably designed network. The term "electronic counter" is here used to refer to the complete apparatus used for this purpose. Because of the low inertia of electronic systems, such a counter is capable of a counting speed thousands of times greater than that of the best mechanical counter. A scale-of-10 counter registers every tenth impulse; a scale-of-100 counter (e.g., two scales-of-10 in cascade) registers every hundredth impulse, and so on. Impulses entering the counter are divided again and again through successive units in cascade until the effective number is small enough to be recorded by a mechanical counter, the reading of which is then multiplied by the scale of the electronic counter.

A decimal-system counter consists of a number of elements—units order, tens order, hundreds order, etc.—which tell how many units, tens, hundreds, etc., have been counted. Any order consists of a series or ring of tubes which are rendered conducting (and later, nonconducting) sequentially and repeatedly as successive impulses are fed to the order. One of the tubes in a ring is arranged not only to become conducting in its proper sequence, but also to pass an impulse on to the next higher order, so as to record the number of times the complete ring has been traversed. At the end of a counting period, the count received by the order is determined by the number of complete traversals (indicated by the next higher order) and the position of the final conducting tube in the ring.

For any order in a counter, the constants of the tubes, the circuit constants, and the type of circuit limit the speed with which one tube can be rendered conducting and the preceding one nonconducting. For any complete counter, the limiting factor in the counting is the speed of the units-order counter which must correctly respond to all impulses; the restrictions on speed and performance of subsequent orders in a cascade are much less stringent. This project was concerned with increasing counting speeds of electronic counters. Accordingly, it was concerned with development of circuits for use as low orders in a complete counter, which would minimize the time involved in changing the conducting states of two successive tubes.

[a] Technical Aide, Sections 17.1 and 17.2, NDRC.
[b] Technical Aide, Division 17, NDRC.

9.2 MILITARY REQUIREMENTS

When this work was undertaken electronic counters were available which would count accurately as many as 20,000 regularly spaced electric pulses per second using the decimal system, or 220,000 pulses per second using a scale-of-2 counter. There was no definite military requirement for development of counters with higher speeds, but it was believed that the development of reliable circuits capable of higher counting rates would be a useful undertaking and that valuable applications might result. For example, high speeds would make it possible to divide a time scale into very small units, thus permitting many types of precise measurements otherwise impossible.

The simplest electronic counter is a scale-of-2 type consisting essentially of two tubes which are made alternately conducting by successive impulses. It transmits a single impulse for every two it receives. If n such counters are arranged in cascade they are referred to as a binary counter with a scale of 2^n. Such a counter is speedy, but, since it reports in powers of two, its readings are not convenient for interpretation. A more simple but less speedy arrangement is a decimal system reporting in powers of ten. Accordingly, there was placed on the research the additional requirement that the system developed be a decimal one. The initial objective in the work aimed at a reliable counting speed of 500,000 impulses per second (ips).

9.3 SUMMARY OF DEVELOPMENT

Originally, contracts were entered into with the Massachusetts Institute of Technology,[18-22] the University of Chicago,[14,17] and the National Cash Register Company[1-7] for the development of ultra-high-speed electronic counter circuits. Each contract required the submission of one or more sample counters. Under the three contracts, various circuits were considered and tested sufficiently to estimate their possibilities. These are discussed in Section 9.5 under History. Ultimately the first two contracts were terminated and work was concentrated under a contract with the National Cash Register Company. Resulting from these original contracts, a new contract[8-13] was written with the National Cash Register Company, under which applications of the counter circuits were to be developed.

The final decimal counter developed under this project has six orders, so that a total accumulation of 999,999 is possible. The units order is a scale-of-16 binary counter which is reset to zero at every tenth impulse. This counter has a speed of 4,000,000 ips when operating as a true scale-of-16 counter and of 1,500,000 ips when operating as a scale-of-10 counter. All but the units order are gas-tube counters with lower speeds. Including all orders, the counter has a *reliable* counting speed of 1,000,000 ips, or possibly slightly higher.

In order to test the accuracy of this counter, an instrument was developed to generate sine-wave trains of a predetermined number of cycles. By use of it there may be applied to the counter by a 1-mc signal a known number of pulses varying from 1 to 999,999. A high-frequency oscillator is used with a "gate" tube, which effects the initiation and termination of the megacycle signal on the transmission line. The gate tube is controlled by a "start" and a "stop" gas triode, which is activated by a local counter when the predetermined number of impulses is reached.

Since electronic counters provide a means of determining the number of discrete, rapidly recurring electric impulses, they can be used as translation devices in an intelligence transmission system, the intelligence being conveyed by the number of impulses comprising a group. A system was devised for transmitting by radio to a receiver-counter any number from 1 to 99,999. The maximum time the transmitter is on the air broadcasting any number is 0.0017 second, or less, so that on ordinary communication receivers the only evidence of transmission of a five-character group is a relatively weak "click." In the receiver-counter there are storage tubes for recording any five 5-digit numbers until read-out is desired. These tubes will "remember" a number indefinitely, until they are cleared by the operator of the apparatus. Furthermore, the system will refuse to receive numbers when there are no tubes available for storage.

In connection with the development of the high-speed counter, an electronic gate circuit was developed to make possible the measurement of the interval between two electrical impulses. The two impulses open and close a gate feeding megacycle pulses into the counter. The precision in determining the interval between the two impulses depends on that of the frequency being fed to the counter with the possible error of ± 1 microsecond introduced in the gate circuit itself.

The original system was delivered as an experimental unit to determine its usefulness to the Aberdeen Proving Ground where the Ordnance Department found that its accuracy and adaptability warranted the procurement of additional models because the counter and associated gate circuit mentioned proved useful in the measurement of muzzle velocities of various sizes of shells.

The communication system was demonstrated to numerous Service personnel in late 1942 and early 1943 but the consensus was that there was no requirement for the apparatus.

In connection with this work, circuit and theoretical data were furnished to various NDRC groups as well as for Service uses.

9.4 DESCRIPTION AND TECHNICAL INFORMATION

9.4.1 Ultra-High-Speed Decimal Accumulator[7]

The wiring diagram of the complete *high-speed decimal accumulator* [HSDA] is given in the contractor's report.[7a] The instrument con-

sists essentially of an assembly of five sections: the power and control, the indicator, the units-order high-speed resetting binary counter, the units-order decoder, and the gas-tube counter.

The units-order counter, which makes the high speed possible, resulted from development work on a high-speed *resetting binary counter* [RBC] originally suggested under the contract livers negative impulses to that stage which converts the sine waves into the required step impulses.

The first scale-of-2 stage of the RBC operates on every input impulse; the second, on every second impulse; the third, on every fourth impulse; and the fourth on every eighth impulse. Each stage is in its zero position when its *A* tube

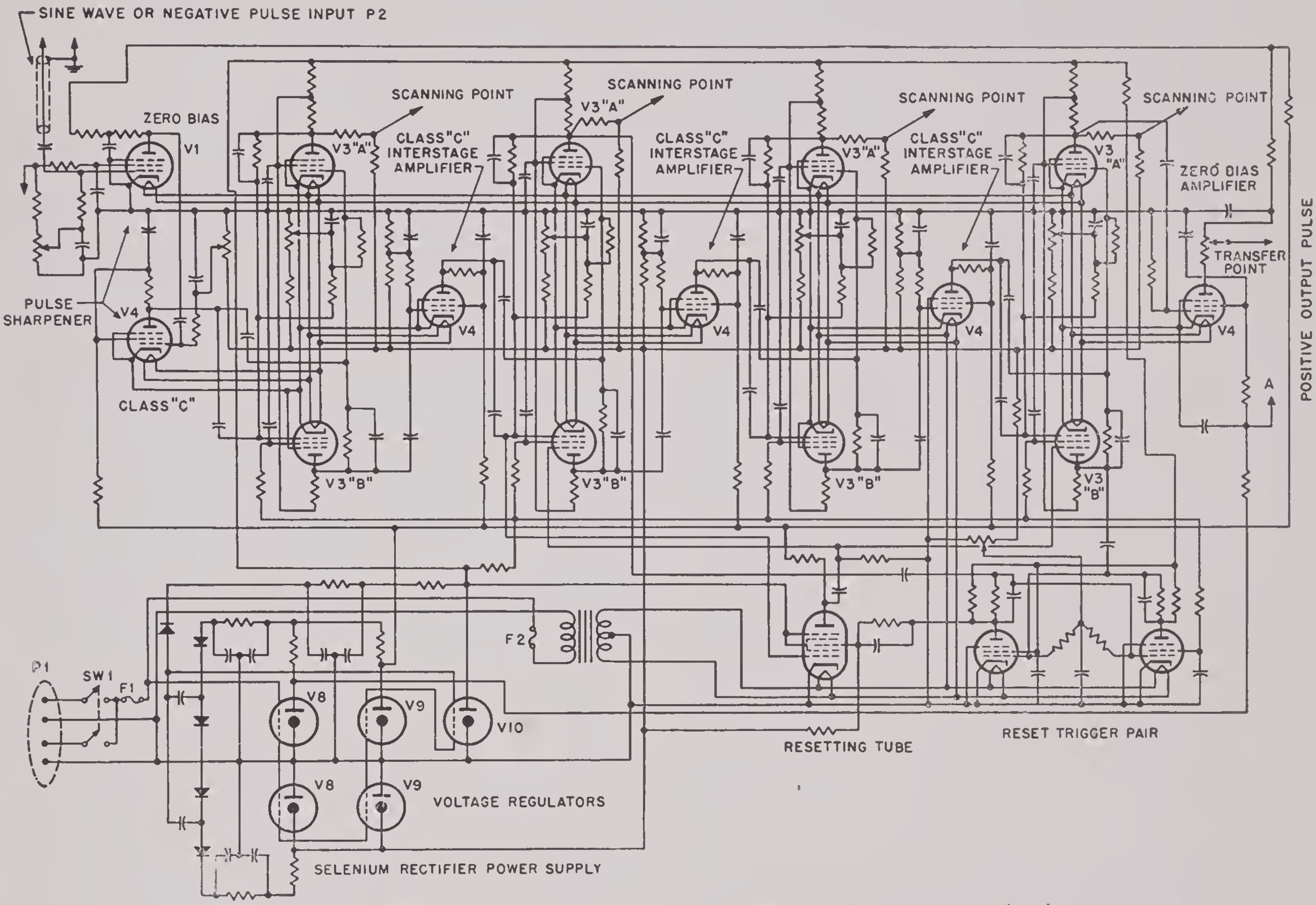

FIGURE 1. Wiring diagram of final design of resetting binary counter circuit.

with the University of Chicago.[14] Figure 1 shows the elements of the final design of the RBC circuit.[7b] (It was modified somewhat on incorporation in the HSDA, but this figure serves to indicate the method of operation.) Basically the RBC is a scale-of-16 counter (i.e., four scales-of-2 in cascade) with interstage discriminators and recycling system which resets the counter to zero at the tenth count. A transfer impulse to the next higher denominational order is effected every tenth count (i.e., every time the counter resets or recycles). A two-tube impulse shaper precedes the first stage of the counter and delivers

is conducting. After a count of eight, the *B* tube of stage four will be conducting; and after nine, the *B* tubes of the fourth and first stages. The tenth count triggers the first stage to its zero position, initiating a signal to the second stage which triggers from *A* to *B*.

The RBC now resets; that is, the second and fourth stages trigger back to the *A* position, stages 1 and 3 being already there. Resetting is accomplished by applying a negative impulse to the suppressor grids of tubes 2B and 4B (which are conducting at a count of 10) from the resetting tube V7, which conducts each time

4B and 2B are conducting. The negative impulse renders tubes 2B and 4B nonconducting, which makes 2A and 4A conducting and thus effects the resetting.

The units counter of the HSDA has a maximum counting speed of 4,000,000 ips when operating as a true scale-of-16 binary counter. This high speed is obtained by reducing tube and distributed capacities to a minimum, and selecting a tube having a very low plate resistance. The counter has a maximum speed of 1,500,000 ips when operating as a scale-of-10 counter. The resetting system limits the scale-of-10 speed.

The complete HSDA has six orders, so that a total accumulation of 999,999 impulses is possible. Suitable arrangements are made for transfers of impulses from each decade to the one of higher order. All but the units order are gas-tube counters. The circuit shown in Figure 9 is essentially that used for the tens-order counter, which operates at 100,000 ips when the input signal is 1,000,000 ips. (There was some modification of this circuit in connection with its incorporation in the HSDA; e.g., addition of another tube for transferring impulses to the hundreds order, etc.) The hundreds-, thousands-, ten thousands-, and hundred thousands-order gas-tube counters are lower-speed thyratron rings with a maximum speed of 15,000 ips. These orders differ from the tens order only in circuit constants. At the termination of a counting period, the count which is retained is indicated by an electromechanical indicator, which senses the counters and indicates the ignited tubes. The units-order counter, however, has its count retained in the binary system of notation, and it is therefore necessary to decode or translate the binary notation to the decimal notation so that the decimal indicator can sense the resulting decimal values.

9.1.2 Controlled Impulse Generator[7c]

A complete wiring diagram for the controlled impulse generator is given in the contractor's report.[7d] It generates groups of from 1 to 999,999 impulses at the rate of 1,000,000 per second. It consists of a self-contained power supply, a relay-control system, an ultra-high-speed accumulator, a six-column keyboard, a high-frequency oscillator, and a start-stop system associated with a gate tube.

The generator accumulators are counterparts of those used in the receiver, with one important exception: whereas the receiver-counter rings start on zero and advance to some other position, the generator counters can be started anywhere, and always end on the same position, which is a specified capacity of the accumulator. When that position is reached a stop tube closes the gate tube, which removes the signal from the receiver counter. In operation, the setting up of a number on the keyboard of the generator conditions the tubes in the generator's accumulator so that the accumulator merely needs to count that number to reach its specified capacity (i.e., setting up a number ignites tubes in the accumulator to indicate that the complement of that number *has already been counted*).

The application of the indicated number of impulses to the receiver-counter is controlled by a gate tube, an 1852 used as a suppressor-modulated Class A amplifier, whose output is supplied to the local accumulator and also to the output terminal. The suppressor is modulated by a square wave furnished by two gas tubes known as start and stop respectively. When the start tube becomes conducting it makes the suppressor of the gate slightly positive and permits radio frequency to appear in the plate circuit. Firing of the start tube is synchronized with the r-f voltage on the grid of the 1852 so that only full cycles can be sent out, thus insuring that the first cycle will be counted. When the capacity of the accumulator is reached (i.e., when the number of impulses set up in the keyboard has been transmitted) the stop tube biases the gate's suppressor beyond cutoff and no further impulses are transmitted.

9.1.3 Electronic Counter Communication Device[11]

The *electronic counter communication device* [ECD] consists of three units: a pulse-producing device or modulator (for wiring diagram see Figure 2 of the contractor's report[11]), a radio transmitter (Figure 4 of the contractor's report[11]), and a wide-band radio receiver with associated counter circuits and read-out devices (Figures 7, 11, 12, 13, and 14 of the contractor's

report[11]). The arrangements of the impulser, of the impulse counter, and of the storage tubes and indicator are shown in Figures 2, 3, and 4 below.

The modulator has a keyboard (Figure 2) similar to that found on computing machines, consisting of five columns of keys numbered 1 to 9. Each key has a small thyratron tube associated with it and each column of keys has also two spare thyratrons, one for the digit 0 (for which there is no key) and one to transfer the electric indications from one decade to the next. The modulator, therefore, has a total of 55 small thyratrons, plus associated power-supply circuits, amplifier circuits, and pulse-sharpening circuits.

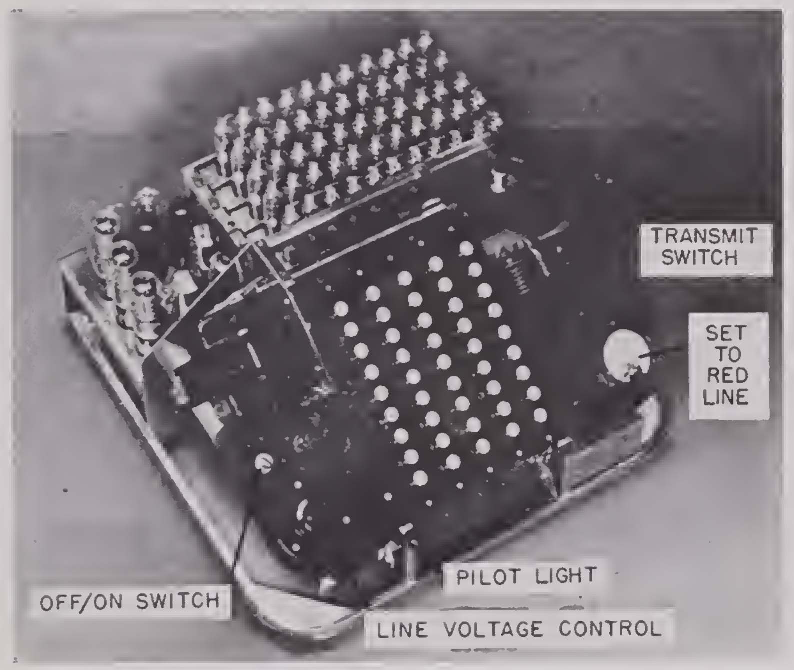

FIGURE 2. View of impulser and keyboard.

Any desired 5-digit number is set up on the keyboard and is sent by depressing a "send" key. The depression of that key initiates a train of impulses produced by the miniature thyratrons and their associated RC coupling circuits. These pulses occur at a rate of 40,000 per second, with time spacing between the indications of various decade banks to allow transfer of circuits from one bank to the next. The total transmission time required for any 5-digit number is 0.0017 second, or less. This is possible because a decimal system is used. A number such as 99,999 does not require the generation of 99,999 pulses; it requires only 55 pulses, that is, nine pulses for each decade, plus an extra pulse in each decade to represent the zero key, plus a transfer pulse for each decade.


FIGURE 3. Impulse counter.

The pulses so produced are applied to an r-f transmitter operating at 7 mc. After being transmitted by radio carrier, the signals are received in a wide-band superheterodyne receiver, and are then applied to appropriate counting circuits (Figure 3). These counting circuits are practically identical to the pulse-producing circuits in the modulator. The count made by these circuits in any decade is applied electrically to a multi-section storage tube, which remembers the number of counts received. This "memory" is accomplished by tripping one of the thyratron sections of the storage tube in accordance with the count received. This section of the storage


FIGURE 4. Electronic storage chassis and mechanical read-out dial.

tube remains conducting until the plate voltage is removed by opening a switch manually after the read-out.

The final indication of the number received, counted, and remembered by the apparatus is obtained on a mechanical read-out dial (Figure 4) which indicates the sections of the various storage tubes conducting at the time the number is read. There are sufficient storage tubes incorporated in the apparatus to allow the indication of any five 5-digit numbers. This means that 25 numerals from 0 to 9 can be remembered simultaneously and read out at will on the mechanical system. The storage tube will remember a number indefinitely until it is cleared by the operator. Furthermore, the system will not receive numbers when tubes are not available for storage.

For coded communications it would be preferable to have a system in which numbers from 0 to 25 could be counted and stored. Such a system could be built up. A system built on a base of 9 rather than 25 was developed because storage tubes with 10 sections were readily available.

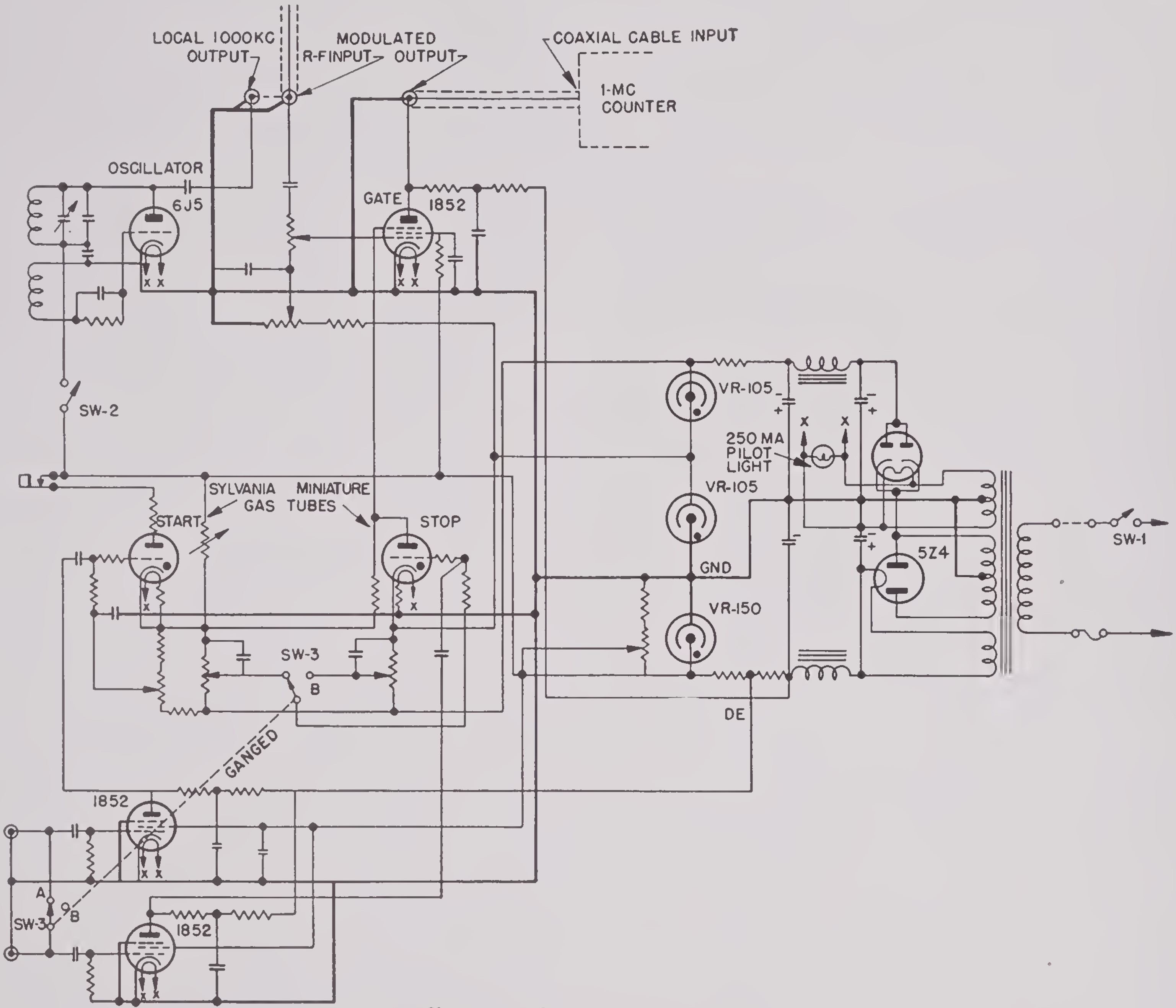

FIGURE 5. One-megacycle gate.

9.4.4 Electronic Gate Circuit[12]

The wiring diagram of the *high-speed counter auxiliary one-megacycle electronic gate* [EG], for measuring the interval between two electric impulses, is shown in Figure 5. Essentially, the EG is an 1852/6AC7 amplifier stage through which the megacycle frequency is fed to the counter unit. The 1852 is arranged for suppressor modulation by a square wave which is generated by two miniature thyratrons controlled by the interval-marking pulses. The suppressor

of the EG is normally held sufficiently negative to prevent conduction. Upon receiving the start signal, the suppressor is swung slightly positive and the stage operates as a normal Class C amplifier. Application of the stop signal causes the suppressor to be returned to its cutoff potential and the 1-mc output of the stage disappears. The number of cycles passed during the interval is counted by the high-speed counter and serves to determine the time interval. The accuracy is ±1 microsecond.

beam from the gun moves along the axis of the tube and is deflected by B and D, so that the electrons must move on the surface of a cone. In addition, the B segments have the proper electric potentials to keep the electrons in a pencil beam and directed in such a way as to strike the region which is clockwise from the supporting lead of one of the collecting grids C. Once the electron beam is directed on a certain C element, it continues to strike at that portion of the element as long as all potentials remain un-

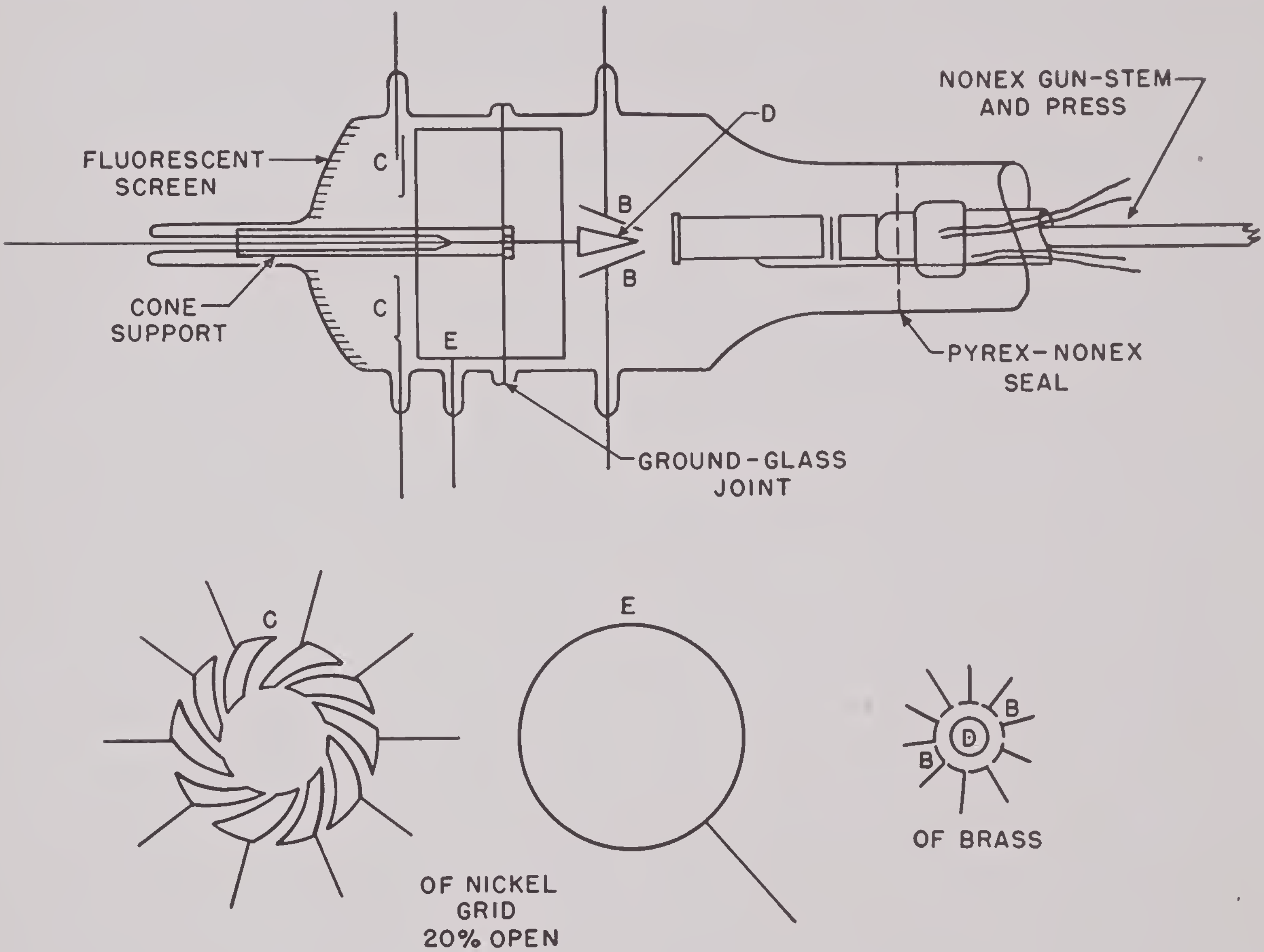

FIGURE 6. Electron ratchet tube.

changed. If a positive pulse is applied to the central cone, the electron beam will be pulled in along a radius and will strike the C element which is next in a position clockwise to the one from which it departed. When the beam strikes the new C element, potentials adjust themselves automatically to move it clockwise on the element to a position where a positive impulse on the cone will move it in to strike the next C element. Each positive impulse moves the beam

9.5 HISTORY

In work leading up to the final circuits, a number of ideas and circuits were considered and tested, and it is felt that they merit some discussion.

9.5.1 Electron Ratchet Tube[14a]

One of these ideas was the *electron ratchet tube* [ERT], as illustrated in Figure 6. This was suggested by the University of Chicago. An electron

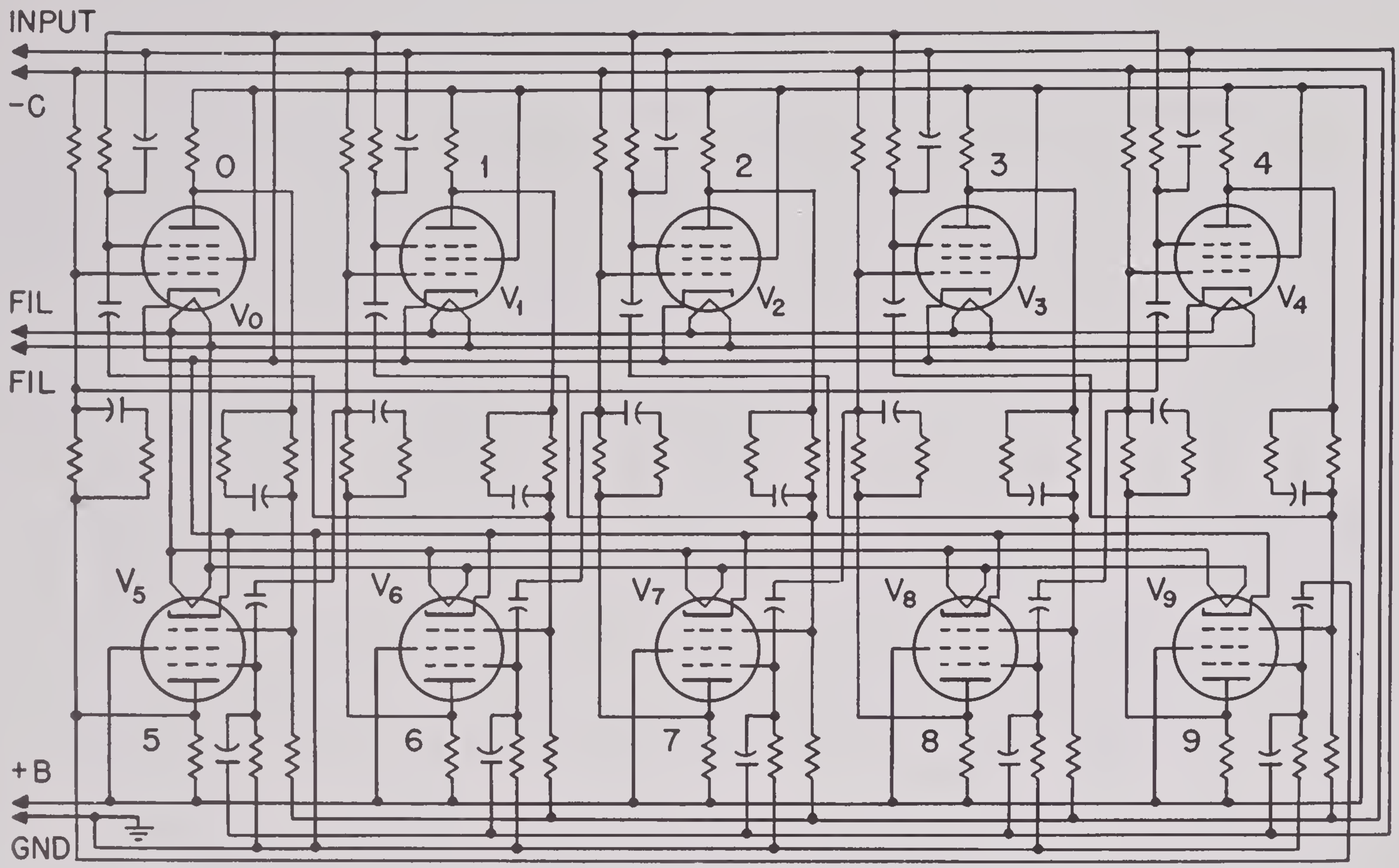

FIGURE 7. Conjugate-pair counter.

forward one element. The tube could therefore be used for a counter, with one *C* element arranged to transmit an impulse to another decade each time the beam struck it. By a slight alteration of the shapes of the *C* elements arrangements could be made for positive pulses to cause clockwise rotation, and negative pulses to cause counterclockwise rotation. A model tube of the clockwise type was constructed but time was not available for testing it as a high-speed counter.

9.5.2 Conjugate-Pair Counter Circuit[7e]

Figure 7 is the circuit diagram of a scale-of-10 counter, a configuration of ten high-vacuum tubes arranged in five interconnected trigger pairs. Five of the ten tubes are always conducting. In the early research the circuit showed promise of responding to high impulsing rates, but other types of counter circuits later superseded it. The highest counting speed observed during the tests of this circuit was 300,000. It was felt that with further development a special vacuum tube might enable the circuit to operate at 1 mc.

9.5.3 Dekatron Counter Circuit[7f]

This circuit, shown in Figure 8, was one of the early ones considered. It is a seven-tube scale-of-10 counter — an arrangement of a scale-of-2 counter cascaded with a scale-of-5 counter. The scale-of-5 section is the novel part of the circuit. One tube of the five is held in a conducting state by the joint action of the four nonconducting tubes. In a sense, the circuit is a trigger circuit with one tube acting as the complement of the other four. The counter is read-out by an electromechanical indicator through a decoding network. This counter operates well at 25,000 ips.

9.5.4 High-Speed Thyratron Counter Circuits[7g]

Previous thyratron scale-of-10 circuits relied on grid priming and extinction by cathode coupling for operation, thus limiting the counting speed to that determined by the deionization time of the previous tube. By introducing a new method of anode extinction through the use of a single common anode resistance and individual cathode condensers, tube deionization does not have to be completed until it is again time for that tube to conduct, increasing the limiting speed by a factor equal to the number of tubes in the ring — in this case, ten. Further increases in speed are made possible by reducing the de-

ionization time of the tube, which can be accomplished by changing the gas pressure and electrode size and spacing.

A scale-of-10 counter involving the above features was developed. It operated well at 100,000 ips and would count at higher speeds if anode, grid, and heater potentials were carefully controlled. The counting speed of a gas-tube counter can be doubled by inserting a scale-of-2 counter ahead of the gas-tube counter. Thus it is possible to count at 200,000 ips by using a scale-of-2 high-vacuum counter and a scale-of-5 thyratron ring, the combination being a scale-of-10 counter. To improve tube life this circuit was later changed so as to operate at the same speed with smaller grid potentials. The resultant circuit, which is the basis of the tens-order counter in the HSDA, is shown in Figure 9.

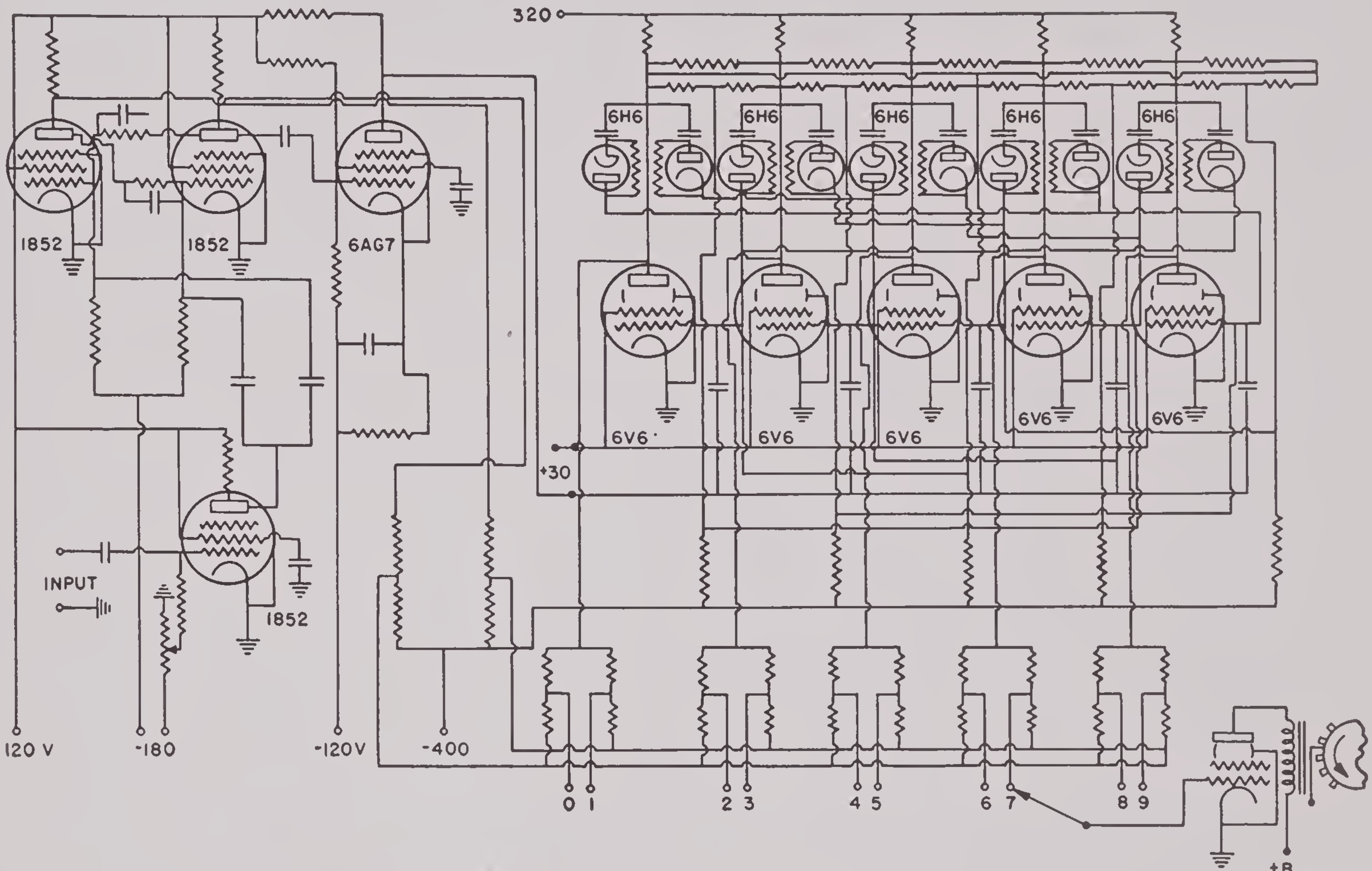

FIGURE 8. Dekatron seven-tube scale-of-10 counter.

9.5.5

Medium- and Low-Speed Thyratron Counters[7h]

In many applications it is not necessary to provide thyratron counters with speeds greater than 10,000 ips, such as when the ring is used as the 10^2, 10^3, 10^4, and 10^5 denominational order counter in a multiple-decade counter. Accordingly, a thyratron counter with a top speed of about 12,000 ips was designed. It is comparatively simple to design such a counter with a tube grid bias during conduction of only —15 v. This counter has the same configuration as the higher speed gas-tube counters, but different circuit values. Another gas-tube counter of medium speed was developed, operating at 50,000 ips with —20 v on the grid of a conducting tube. This counter differs from the high-speed ones only in circuit constants. All the counters use the miniature thyratron designed for high-speed operation.

9.5.6

Binary to Decimal Converter[7i]

This development consists of a binary counter of many stages wherein the complete count is received, and a translater or converter which impulses the binary count into a decimal accumulator or totalizer after the counting period has ended. Counting can be done with this circuit at 4 mc. Approximately 1 second is required for conversion.

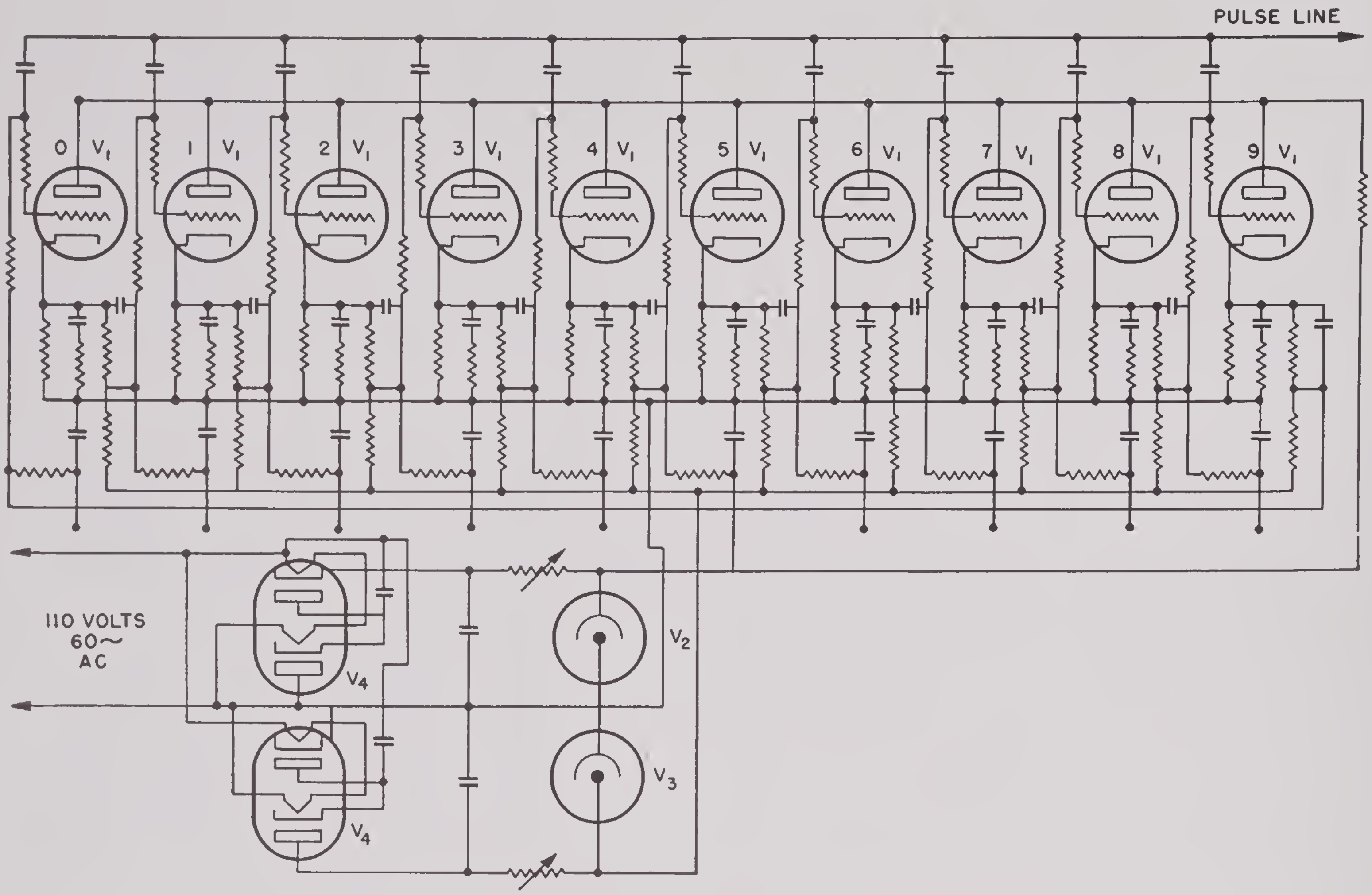

FIGURE 9. High-speed thyratron counter circuit.

9.5.7 First Counter Model[7j]

The wiring diagram of the first counter model developed by the National Cash Register Company is given in the contractor's original report.[4]

The units-order counter comprises a scale-of-2 followed by a scale-of-5 gas-tube counter. The tens- and hundreds-order decades are thyratron rings of ten tubes each. A motor-driven electromechanical indicator senses the counter decades and indicates the counts after the counting period. After each count the instrument can be reset to zero by operating the relay system which is a part of the instrument.

Chapter 10

DEVELOPMENT OF METHODS FOR DETECTING DEFECTIVE ROTATING BANDS ON PROJECTILES[a]

By *Clark Goodman*[b]

10.1 INTRODUCTION

THE OBJECT of this investigation was to develop a nondestructive production method for detecting improperly banded projectiles. The gilding-metal band serves as a seal to prevent the escape of the powder gases past the shell, and to impart rotation to the shell as it is forced through the rifling of the gun barrel. Improperly seated bands have a marked effect upon the muzzle velocity of the shell, and this results in a wide dispersion in the range of the projectiles.

10.2 BANDING

The clearance or gap that exists between the band and its seat in improperly banded shells may take one of several forms.

1. The band is pressed firmly against the knurling on the band seat but has not been forced down against the band seat between the knurls.
2. The band is loose at all points. It not only does not make contact with the band seat, but also has sprung away from the knurling.
3. The band is not coaxial with the shell body; that is, it may fit tightly at one edge of the band seat while clearance exists at the other edge.

In general, the clearance, whatever its type, is not uniform about the circumference. Values of clearance amounting to as much as eight or ten mils and even more have been found in poorly banded shells.

A uniform clearance of one mil around the circumference of a shell is equivalent to a reduction in the outside-band diameter of two mils. Tests at proving grounds have shown that a variation of band diameter in properly banded shells also affects the muzzle velocity and range of the projectile. A shell having a tightly seated band, 4.218-in. diameter, would have a muzzle velocity practically identical with a shell having a poorly seated band of 4.220-in. diameter and an average clearance around the circumference of 1 mil. The Ordnance Specifications permit a variation in band diameter of ± 0.003 in. from a nominal outside diameter of 4.220 in. When a shell is fired which has either clearance underneath a band of the correct diameter or has a tightly seated under-sized band, full powder pressure is not applied to the shell, and there is a clearly defined flash of burning powder at the muzzle and the velocity of the projectile is below normal. If the shell band is of the correct diameter and is properly banded, then the flash is not observed inasmuch as the powder is completely consumed before the shell leaves the gun.

The effect of band clearance on the muzzle velocity of a 105-mm shell amounts to a reduction of 2.6 (Aberdeen Proving Ground) to 3.2 (Southwestern Proving Ground) fps per mil of clearance at a muzzle velocity of 1,030 fps. Therefore, the effect of a variation of 1 mil in band diameter would produce approximately 1.5 fps change in muzzle velocity.

10.3 PROBABLE DISPERSION OF MUZZLE VELOCITY

In addition to banding, other factors produce variations in muzzle velocity. The most important of these is the powder. The proving grounds report that powder irregularities account for a variation of ± 7 in a muzzle velocity of 1,030 fps. It is evident, therefore, that as a result of variations in banding and powder one may expect a dispersion in muzzle velocity of approximately ± 12 in a velocity of 1,030 fps in correctly banded shells whose band diameters conform to the allowable specification limits. Tests at the proving grounds show that more than 95 per cent of the good shells have a muzzle velocity within ± 10 fps of the reference shells.

It should be observed, therefore, that the ability to detect variations in muzzle velocity due

[a] OD-151.
[b] Technical Aide, Division 17.

to poor band seating is dependent upon the possibility of correcting for or taking into account the variations in velocity resulting from the foregoing causes.

10.4 METHODS INVESTIGATED

The following methods were considered but did not progress beyond the laboratory stage: air leakage test,[1] ball rebound test,[1a] heat flow method,[1b] and supersonic tests I and II.[1c] A number of other methods were tested and rejected as unsuitable for production tests. These include the Herzog test,[3] the inductance method,[1d] an acoustical test,[1e,3a] current and potential contact tests,[1f,3b] and thermal tests.[1g,2,3c]

Herzog Test. This method was suggested by Gerhard Herzog of The Texas Company. In this method a ⅛-in. hole is drilled through the band and a manometer containing air at a pressure of approximately 25 lb is connected to the hole. Then a cock is opened connecting the manometer to the space underneath the band and the fall in air pressure noted. It is assumed that the fall in pressure will be related to the volume of the air space underneath the band and, therefore, to the average band clearance.

This method, however, is not satisfactory because the clearance is rarely, if ever, uniform around the circumference, and the hole may be drilled at a point in the band where no gap exists. Gaps are seldom continuous and, even in tight bands, there is often some leakage of air at the edge of the band. Therefore, the test was not carried beyond the laboratory stage.

The Inductance Method. In the inductance method, the change is measured in the inductance of a coil placed around the band of a shell. This method was tried over at a wide range of frequencies in both the laboratory and at the Southwestern Proving Ground. As no correlation was found to exist between the muzzle velocities and the inductance values, the method was discarded.

Acoustical Test. The acoustical method was described in the Progress Report of May 25, 1944. The sound-testing equipment was taken to the Southwestern Proving Ground, where several hundred shells were given the sound test and fired to obtain their muzzle velocities.

The muzzle-velocity data and the sound results failed to show any evidence of correlation, and the method was discarded as unsuitable.

Current and Potential Contact Test. This method was developed by the Sperry Products, Incorporated, and the first Sperry unit was nearing completion when the School of Engineering at Johns Hopkins University was brought into the picture. The U. S. Ordnance Department was so impressed by the initial results that three Sperry units with their auxiliary equipment were purchased under this contract and furnished, one to the Pittsburgh Ordnance District (Pullman Standard Car Company plant at Butler, Pa.), one to the Aberdeen Proving Ground, and one to the Jefferson Proving Ground. The Aberdeen Sperry unit was sent abroad and used in England for a time. In addition, the U. S. Ordnance Department placed an order for a fourth unit for the Southwestern Proving Ground.

The method was given a thorough field trial. The Jefferson Proving Ground carried out an exhaustive and careful study of its possibilities. The results proved that the method could not be relied upon to separate poorly banded from properly banded shells. It was, therefore, discarded as unsuitable and untrustworthy.

Thermal Test. In this test, the band is coated with an opaque substance that melts at a low temperature. The shell is then placed in a solenoid and subjected to an alternating magnetic field for a short period of time. The resulting current flow in the band heats it but, if the band is tightly seated, the heat flows rapidly into the steel body of the shell and a long time is required to melt the wax or substance used. If there is clearance under the band, then the air gap interferes with the flow of heat, and the wax is quickly melted over such areas.

The method, because of its simplicity, speed of operation, and minimum of equipment requirements, was given an exhaustive study. It was not recommended, however, as a production test because on many tightly banded shells there is dirt, grease, oxides, or a combination of them on the band seat. This foreign material acts as a heat insulator and results in rejection of shells that fire with proper muzzle velocity. If it were feasible in manufacture to keep the band seats and the inside surfaces of the bands bright and clean, the method would be a most useful one.

Although the adoption of the thermal test as a production test of banding is not recommended, nevertheless it is recommended for checking the uniformity of operation of banding presses and similar equipment. It provides a simple, inexpensive method of checking the operation of banding machines.

Two other methods were investigated. The first of these involves the use of an X-ray beam to reveal any clearance under the band. However, it was found that the firing data and the X-ray-measured clearances do not give good correlation. The method requires considerable expensive equipment and a closely controlled voltage supply. It, therefore, is not recommended as a production test for improperly banded shells. The method, however, furnishes a clear picture of any space that exists between the band and its seat, and it is easily applied to the bands of shells of any size. In addition, the apparatus is versatile and has many possible applications. The installation of an X-ray Geiger-Mueller testing equipment at a research center such as the Aberdeen Proving Ground was recommended.

The best correlation with firing data was obtained with a compression test method (the Klipsch test) developed at the Southwestern Proving Ground. It was recommended for adoption as a production test method. In the Klipsch test two shoes, each of the same dimensions and spaced 180 degrees apart, were used. The pressure shoe covers an area of $\frac{3}{8}$x$\frac{3}{8}$ in. and slightly less than 10 degrees on the band of a 105-mm shell. The total pressure applied is slightly in excess of 70,000 psi, and the resulting deformation is measured either by a dial gauge in the testing machine or by a micrometer.

Compression tests have one advantage that none of the other test methods possesses; namely, that they are independent of the presence of oxides and dirt between the band and its seat. If a band is properly seated, these foreign substances are confined under considerable pressure and, therefore, do not affect the firing.

10.5 X-RAY METHODS

The object of this test was to investigate the possibility of using the Geiger-Mueller counter in place of X-ray radiographs which had indicated the feasibility of using X-rays for the detection of improperly banded shells. Radiographs had been taken on a large number of shells at the Iowa Ordnance Plant, as well as elsewhere, and the shells had then been test-fired. Contrary to the tests at the Aberdeen Proving Ground, the muzzle velocity of these shells had correlated well with the average value of air gaps estimated from the radiographs taken at one to three positions on the shells. It was, therefore, thought that an X-ray test which could measure air gaps directly would give an indication of the expected muzzle velocity of the shell.

10.5.1 Apparatus

To adapt X-ray technique to the band-clearance problem and to provide a test that is as rapid, quantitative, and inexpensive as possible, a Geiger counter instead of a photographic film was used to determine the radiation passing through the shell.

The X-ray machine finally used is a 220-kv d-c machine with the tube passing a current of 10 ma. The tube voltage of 218 kv actually used is obtained from a step-up transformer whose primary voltage is approximately 206 v. The primary voltage must be kept constant during a test run, within a volt or two. For this reason, the a-c generator supplying the primary voltage is driven by a d-c motor run from a storage battery. Some means of providing a constant voltage to the X-ray circuit input is essential.

The detailed arrangement of the apparatus was described in Progress Report OSRD 4576. A photograph of the final test set-up is shown in Figure 1. The shell is seen mounted just to the right of the X-ray tube housing, and still further to the right are the collimator and the Geiger-Mueller tube enclosed in its lead housing. Both a direct-reading and a recording milliammeter were available for measuring the output from the counter circuit. This circuit and its associated apparatus are not shown in Figure 1, but the motor-drive mechanism for moving the shell across the X-ray beam is apparent.

10.5.2 Adjustments

A shell, with clearance between its band and band seat, is placed in such a position that the X-ray beam passes through the band only. As the shell is moved further into the beam until the

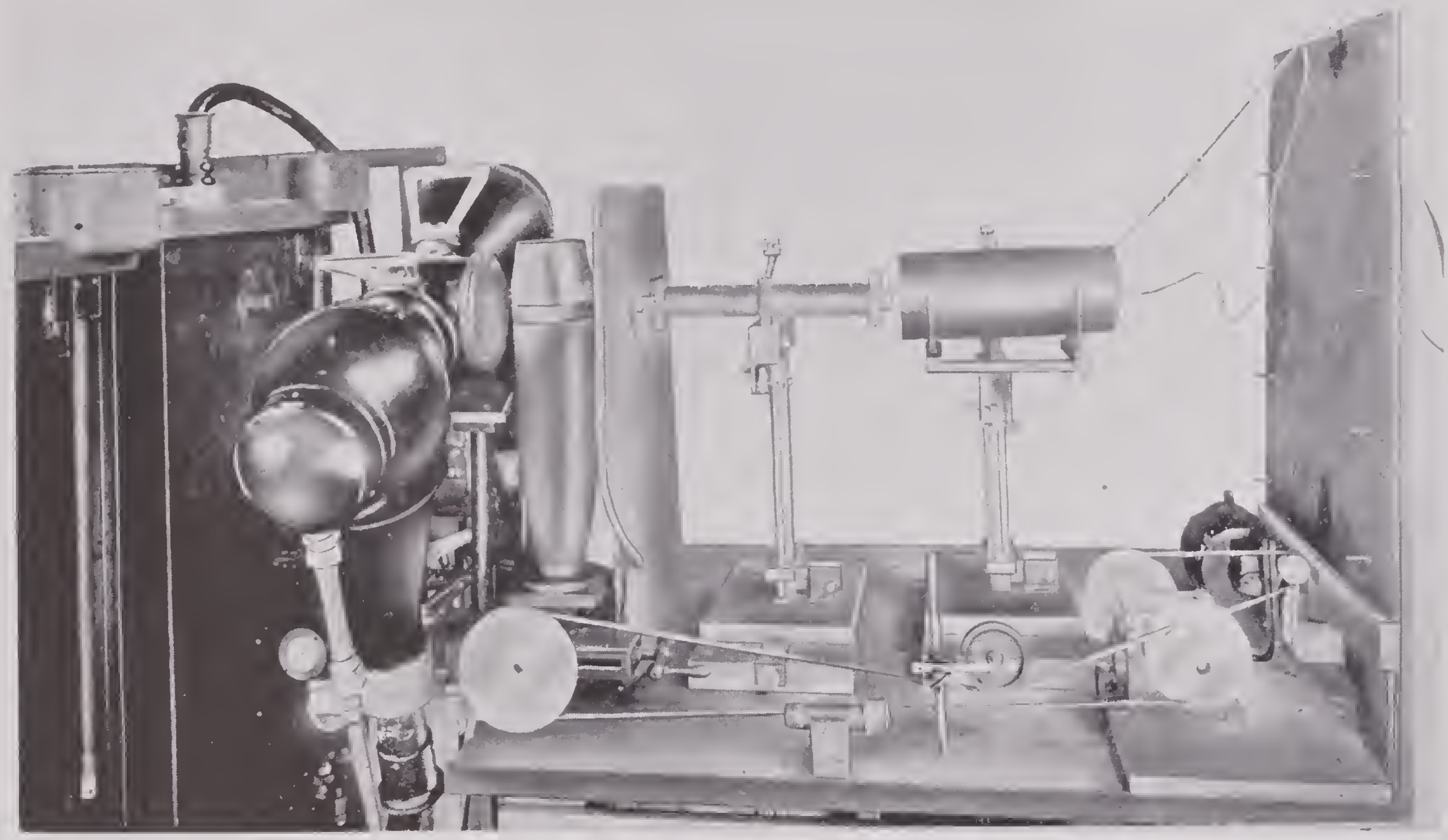

FIGURE 1. Arrangement of apparatus for X-ray method.

latter passes through both the band and the steel-shell body, the intensity of the X-ray beam reaching the Geiger tube will decrease to a minimum value, increase to a maximum, and then decrease again. The difference between the minimum and maximum current reading is called the spread and is an indication of the gap between the band and the shell body. It is obviously desirable to test a shell as rapidly as possible without loss of accuracy in measuring this spread. This requires the determination of the best speed for driving the shell across the X-ray beam and the optimum value of capacitance for the integrating capacitor in the counter circuit.

The best combination of shell speed and capacitance is that which gives maximum spread of the milliammeter reading in minimum time without objectionable fluctuation of the needle. For a given shell speed, if the capacitance is too high, the meter does not respond rapidly enough to indicate the complete spread while, if the capacitance is too low, the needle fluctuates to such an extent that the maximum and minimum points cannot be determined accurately. The optimum values were found to be a capacitance of 10 μf and a shell speed of approximately 0.025 in. per minute. This permits a shell to be X-rayed at 36 points in approximately 45 minutes.

The air gap between band and band seat may take any one of several different forms, some being fairly regular and others quite irregular. The problem is further complicated by the ridges in the band seat and the depressions in the band produced in the banding operation. At first, shells were X-rayed at only four points around the circumference. It was soon found that the average spread at these four points might be considerably different from the true average spread of the entire shell, since some very large gaps were found to extend over as little as 10 degrees of the circumference. Such irregular gaps extending for only a few degrees should have little effect on the muzzle velocity of a shell, but they may have some effect, so it was decided to take readings at 10-degree intervals.

In March 1945, 110 shells which had previously been tested by the X-ray Geiger-counter test at the Johns Hopkins University were fired at the Aberdeen Proving Ground. The results of this firing test established that the X-ray test does not give an indication of the muzzle velocity

of a shell. It may be able to separate good lots from bad lots, but its results do not correlate with the firing data for shells of a single lot. This seems to indicate that the air gap is not the only factor in the variation of muzzle velocity in the shells tested.

10.6 KLIPSCH COMPRESSION TEST

The Klipsch compression test is based on the assumption that any air gap beneath the rotating band may be measured by forcing the band down against the shell body and measuring the resulting deformation of the band. This forcing is accomplished by placing the shell in a compression machine with its band between two diametrically opposite shoes and applying a predetermined load. The investigation at the Southwestern Proving Ground has shown that 3/8-in. square shoes or anvils, with faces curved to fit the rotating band are suitablefor applying the test to 105-mm shells, and that a load of between 10,000 and 11,000 lb, equivalent to approximately 75,000 psi on the band, gives satisfactory results.

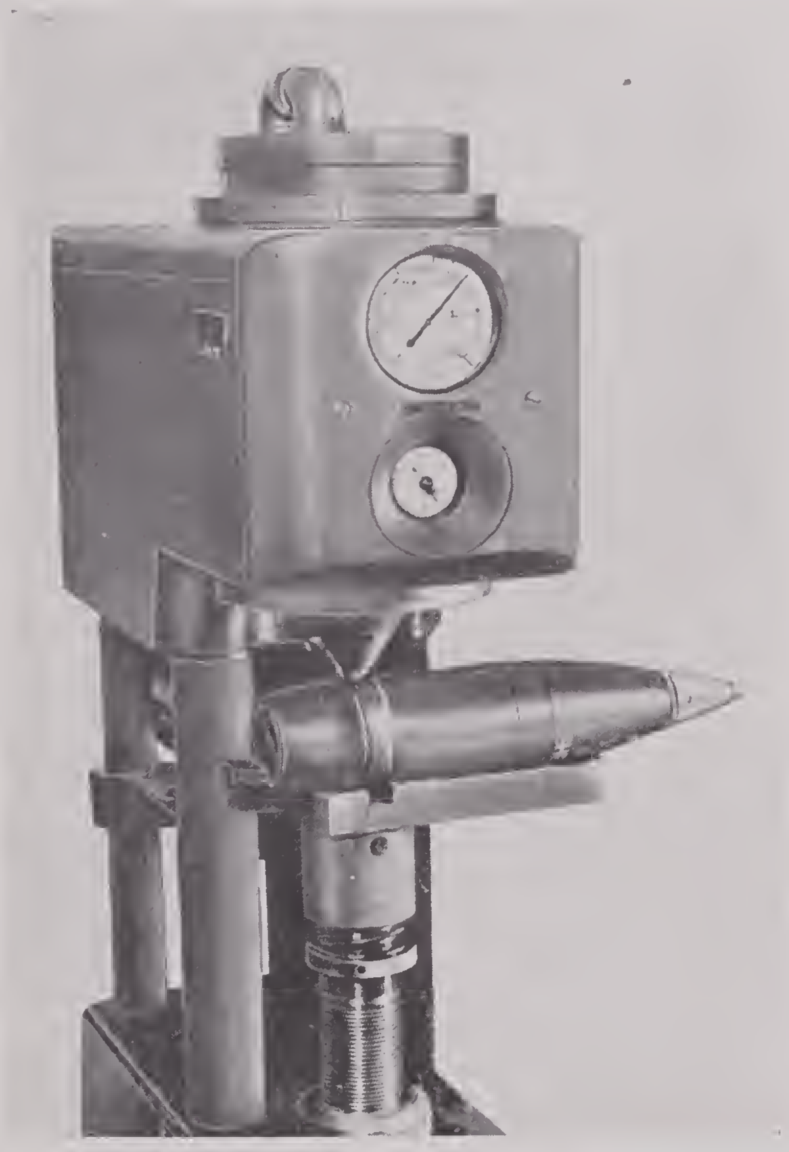

Figure 2. Machine used in Klipsch test.

In the Klipsch test, the shell is compressed at five positions taken at 36-degree intervals around the circumference of the band, and the resulting deformation determined for each position. The machine, which is similar in principle to the standard Brinell tester, is shown in Figure 2 with a 105-mm shell undergoing test. It is of the hydraulic type and the upper gauge in the head is a pressure gauge which reads the load applied to the shoes. A dial gauge for measuring the deformation is mounted below the pressure gauge.

Data obtained with this equipment can be expressed in terms of either indicated clearance, C_I, or indicated looseness, L_I. C_I is the sum of the clearance or gaps between the band and its seat at diametrically opposite points. $L_I = C_I + L_0$, where $2L_0$ is the difference in actual (unpressed) outside band diameter and the nominal band diameter of 4.220 in. L_I takes into account variations in both band diameter and band clearance.

The machine is very simple to operate, and shells are usually handled and tested at the rate of 100 per hour, five deformations being taken on each shell. The cost of the Detroit machine is $2,550.00.

10.7 RESULTS

In Figures 3 and 4, results reported by the Southwestern Proving Ground are plotted for a large number of shells from different manufacturers and different lots, as indicated by the code symbols. These shells were all tested in the Detroit machine and fired. In Figure 3, the indicated clearance is plotted against muzzle velocity, and in Figure 4, indicated looseness against the same quantity. If an indicated clearance of 2 mils is selected as an acceptance limit, then, as seen in Figure 3, the muzzle velocities of the approved shells will range from 1,006 to 1,032 fps and 28 shells whose muzzle velocities fall within the above limits would be rejected as unsatisfactory. If indicated looseness is used as the criterion for acceptance and the limit be chosen as 2.5 mils, then, as seen in Figure 4, the approved shells will vary in muzzle velocity from 1,008 to 1,032 fps and 21 shells with velocities within the above limits would be rejected as un-

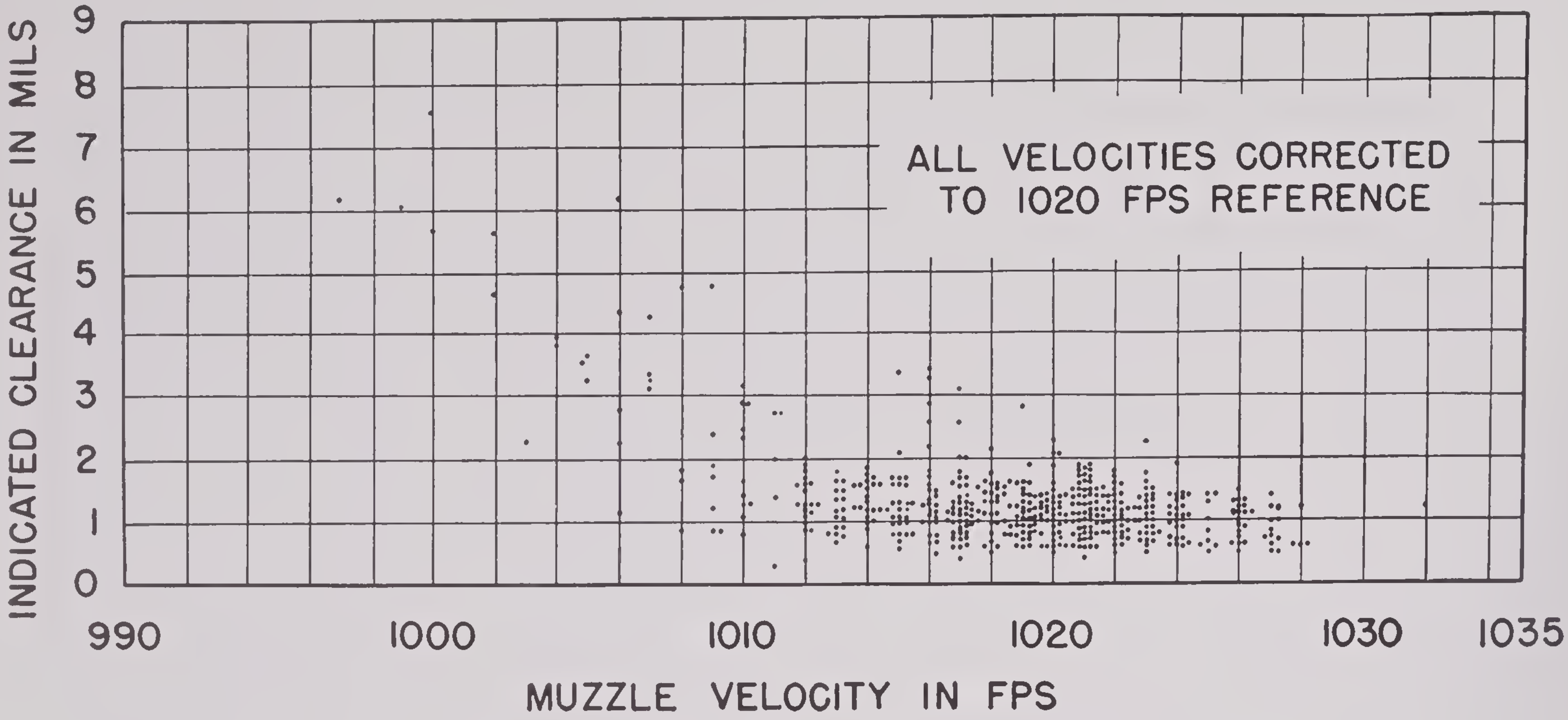

FIGURE 3. Effect of indicated clearance on muzzle velocity.

satisfactory. Actually, the percentage of good shells rejected in both cases is so small that it is negligible. Apparently, therefore, there is little to choose from in determining which acceptance method to use. The odds are, however, slightly in favor of indicated looseness as providing the better production test of improperly banded 105-mm shells.

When this investigation was started in January of 1944, improper banding was the major factor in muzzle-velocity dispersion for 105-mm shells. At the conclusion of this investigation the dispersion attributable to powder variations had become a major factor in the problem. It was believed that, with the experience gained in the band investigation, real and rapid progress could be made in discovering the causes that underlie the powder dispersion.

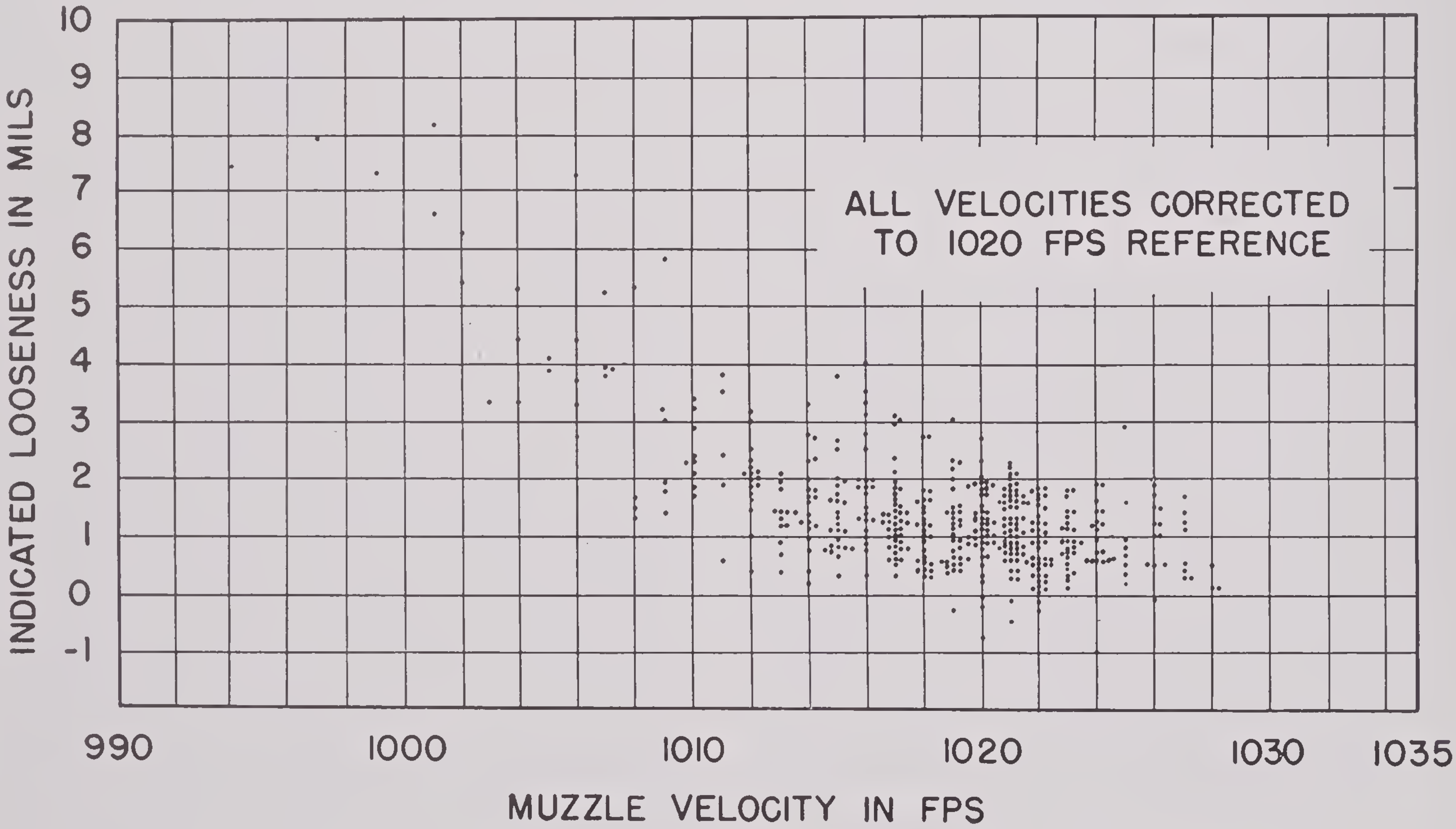

FIGURE 4. Effect of indicated looseness on muzzle velocity.

Chapter 11

HELIUM-PURITY INDICATORS

By *F. L. Yost* [a]

11.1 INTRODUCTION

Two types of *helium-purity indicators* [HPI] were developed to determine the percentage of air impurity in helium gas. The first indicator was for use with fairly large volumes of gas. It was based on the fact that the velocity of sound in a helium-air mixture varies considerably with the percentage of air. The second was for use with small volumes of gas. It was a chemical method based on a distinct change in color of a solution exposed to the helium-air mixture, occurring when the air impurity exceeded a certain marginal amount.

11.2 VELOCITY-OF-SOUND INDICATOR [VSI][1-3]

11.2.1 Introduction

This project resulted from the need of the U. S. Naval Air Station, Lakehurst, New Jersey, for a device for testing the purity of helium in airships. The purposes of purity tests are to determine the amount of helium in the bag when the lift is known and to detect the existence of a leak in which air diffuses into the bag. The purity of the helium varies from 97 per cent to as low as 88 per cent. When an airship is about to start on a long voyage and is therefore carrying a maximum gasoline load, the helium should be as pure as possible; for shorter voyages, the lower purities can be tolerated.

When this project was initiated two types of analyzers were being used at Lakehurst, both based on the fact that the thermal conductivity of helium is about six times that of the oxygen and nitrogen impurities. One type was very accurate as a stationary unit where size and weight were not objectionable, but portable lightweight units proved unsatisfactory. The other type gave very accurate results in the laboratory, but the outfit was very sensitive, bulky and expensive, and was not readily adaptable for installation in an airship ballonet.

[a] Technical Aide, Division 17, NDRC.

11.2.2 Military Requirements

It was desired that an instrument be developed which would simply and rapidly measure 0 to 10 per cent air impurity in helium with an accuracy of 0.5 per cent. It was also desired that the instrument should be reliable over a temperature range of —4 to 95 F. It was further desired that the instrument be reliable and be capable of being operated by a Service man with little previous instruction.

11.2.3 Summary of Development

The work on this project was done at the University of Pennsylvania under Section D3 of the National Defense Research Committee, before the organization of Division 17. The method developed involved the determination of the velocity of sound in helium-air mixtures. Figure 1 shows the way in which the velocity of sound in helium at room temperature varies with the percentage of contamination by air. This velocity is independent of pressure and the effect of temperature is independent of composition. Thus, the ratio of the sound velocity in a known gas mixture to that in an unknown mixture (i.e., unknown percentage) at the same temperature, but at a possibly different pressure, determines the percentage composition of the unknown, independent of temperature and pressure.

The ratio of velocities is equal to the ratio of the resonant frequencies of two identical cavities containing the two gases.[1] A method was developed for calibrating a closed resonating cavity and associated electric circuits so that, for the ranges indicated in Figure 4, the purity of the helium could be determined to a few tenths of 1 per cent from a single dial reading. The cavity is designed to be permanently installed in the airship and, ordinarily, to be open for passage of the airship's helium. When a purity

test is made, the cavity is temporarily sealed to form a closed resonator which contains the trapped sample.

11.2.4 Description and Technical Information

Figure 2 shows the resonating tube assembly.[2] A cylindrical tube was used rather than a closed Helmholtz resonator (consisting of two bulbs

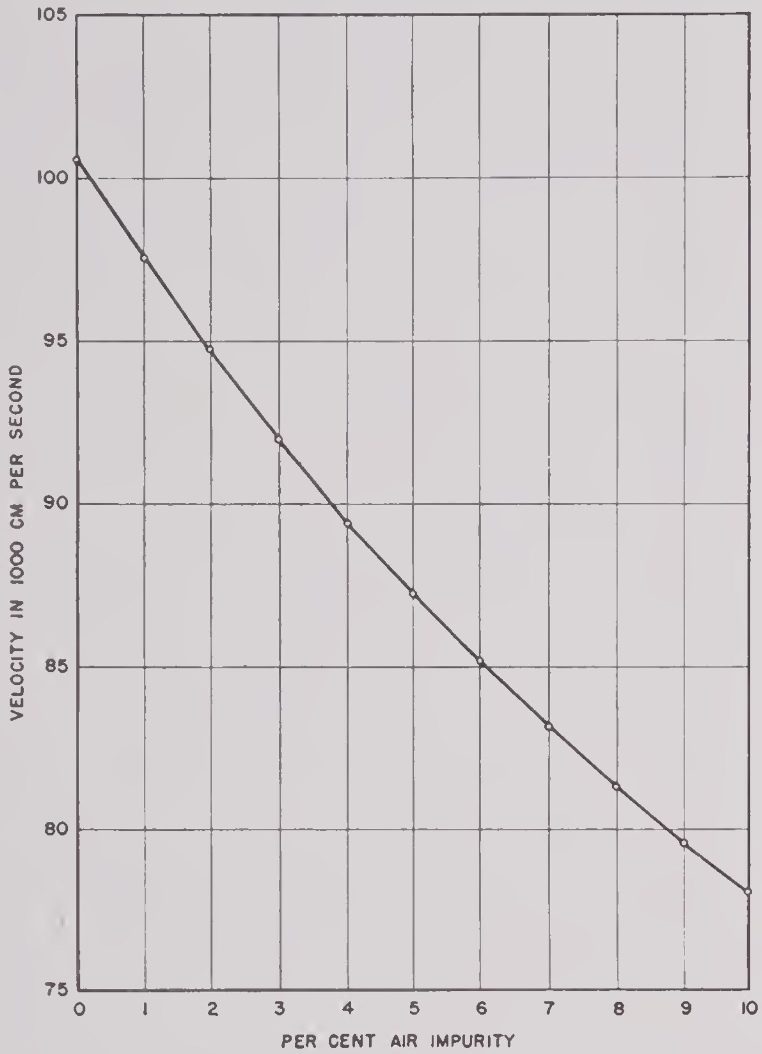

FIGURE 1. Velocity of sound in helium-air mixture as function of percentage of air impurity.

connected by a short neck) because the former allowed more accurate determination of the resonant frequencies. The tube is 42.0 cm long and 7.6 cm in diameter, with a 0.16-cm brass wall closed with a gas-tight flange at each end. To these flanges are bolted removable and identical cups, each containing a crystal earphone to which electric connection can be made through a miniature spark plug and through the vessel itself. One of the earphones is used as a sound generator and the other, as a receiver to detect resonance. Near each end of the vessel is a gas-tight globe valve. On the outside of the tube there is provision for mounting a thermometer, which is a necessary adjunct of the instrument. Finally, there is a receptacle for taking the cable which comes from the electric equipment.

One test unit was to be attached to each ship. The ship's gas would communicate at all times with the vessel so that unless stratification problems arose there would be no question of flushing, and the tube would always be treated uniformly. Samples were to be taken from the bottom of a ship, as was usual practice.

The electric equipment, shown in Figure 3, consists of three parts: (1) an oscillator which generates frequencies between 1,600 and 2,450 c, with the sound-generating earphone placed in the output circuit (the frequency range employed means that the tube is operating on its second harmonic); (2) an amplifier, connecting directly with the detector earphone; and (3) a peak-sharpening circuit, containing the meter which is used to indicate resonances.[2,3]

It was desired to develop an oscillator with a range of frequencies not dependent on temperature and which could be calibrated *absolutely*. Dependence of frequency on temperature is ordinarily due to inductance in the circuit. Accordingly, this oscillator was designed to employ only resistances and capacitances. It was originally hoped that resistances and capacitances which were unaffected by temperature (over the desired range) could be used. However, this was not accomplished. It was impossible to use silver-mica condensers and advance wire-wound resistors, except where absolutely essential. The battery voltages and the paper condensers and carbon resistors actually used varied with the temperature, so that the frequency of the oscillator did depend somewhat on temperature.

To save tubes, a double triode is used as two stages of the three in the amplifier. Large amounts of power are not required, and consequently voltage amplification is the sole consideration, which makes possible the use of small battery-operated tubes.

Without a peak sharpener it is possible to make measurements to a tenth of one per cent. The peak sharpener permits fixing the position of the resonant frequency much more accurately; and, consequently, impurities may be measured with greater ease. Moreover, the

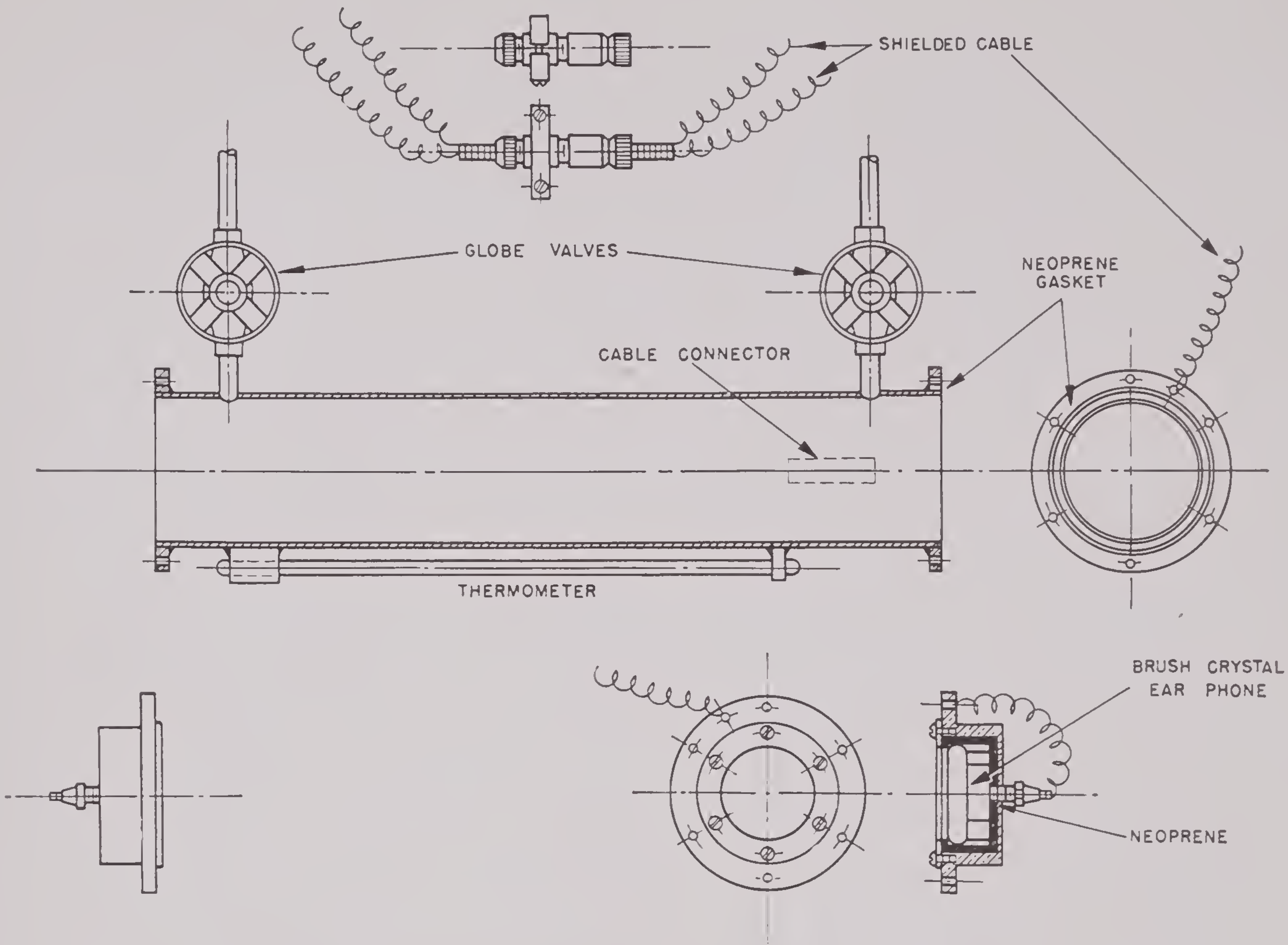

FIGURE 2. Resonating tube assembly for velocity-of-sound indicator.

sharpener has the further desirable property that background noises, either from the exterior or from direct transmission down the tube, are greatly reduced with respect to the main resonances. As a result, only true resonances are evident as the frequency is varied.

The instrument was calibrated by introducing helium-air mixtures of known composition and temperature.[3] Data were taken for a curve of oscillator dial readings against percentage of purity at a given temperature. These data were extended to other temperatures by the well-known proportionality of the velocity of sound to the square root of the absolute temperature. The curves thus obtained, shown in Figure 4, were checked at temperatures between —20 F and 110 F at several different purities. Excellent agreement was found, provided care was taken to thermostat the tube for a few minutes before each reading.

The above calibration was made at room temperature. However, in the field, the electric equipment will be at nearly the same temperature as the tube and the gas, and, accordingly, tests were made on the behavior of the circuit at high and low temperatures. In a range of temperature from a few degrees below 0 to 110 F, the change in frequency of the oscillator amounted to 9 c at a frequency of 2,000 c, which would mean an error of approximately 0.2 per cent in the purity determination. Most of this change is due to a reduction of the battery voltage at low temperatures. With such a small effect it is quite permissible to interpolate the correction on the calibration curves, and this was done.

The presence of water vapor in the gas could only affect the purity determinations if the gas were warm and nearly saturated. Since water vapor could only leak in with the air, there could hardly be enough present to impair the accuracy of the instrument.

Several types of tests were considered before it was decided to use the velocity of sound as a test of purity. Those involving thermal conduc-

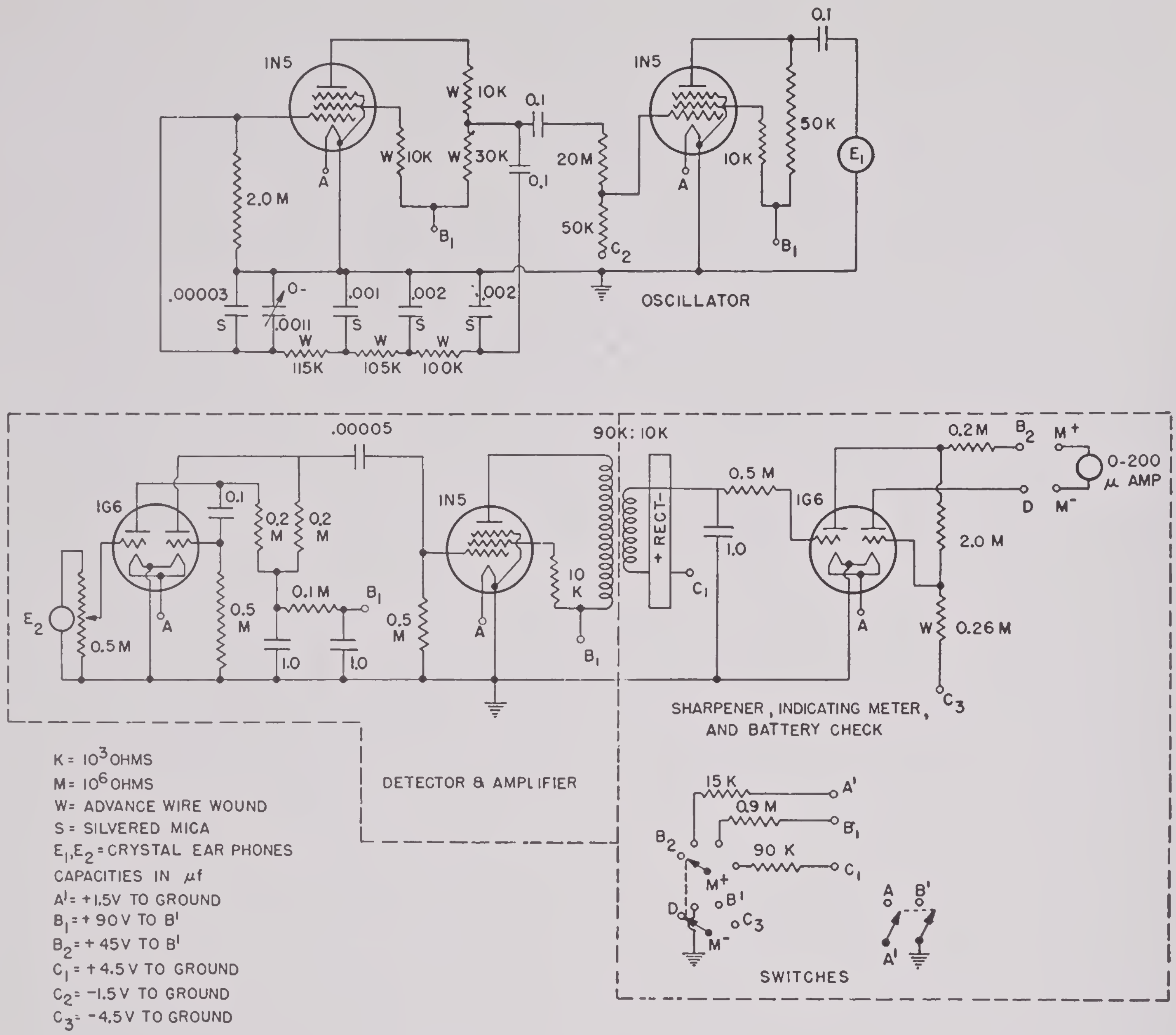

FIGURE 3. Circuit diagram for velocity-of-sound indicator.

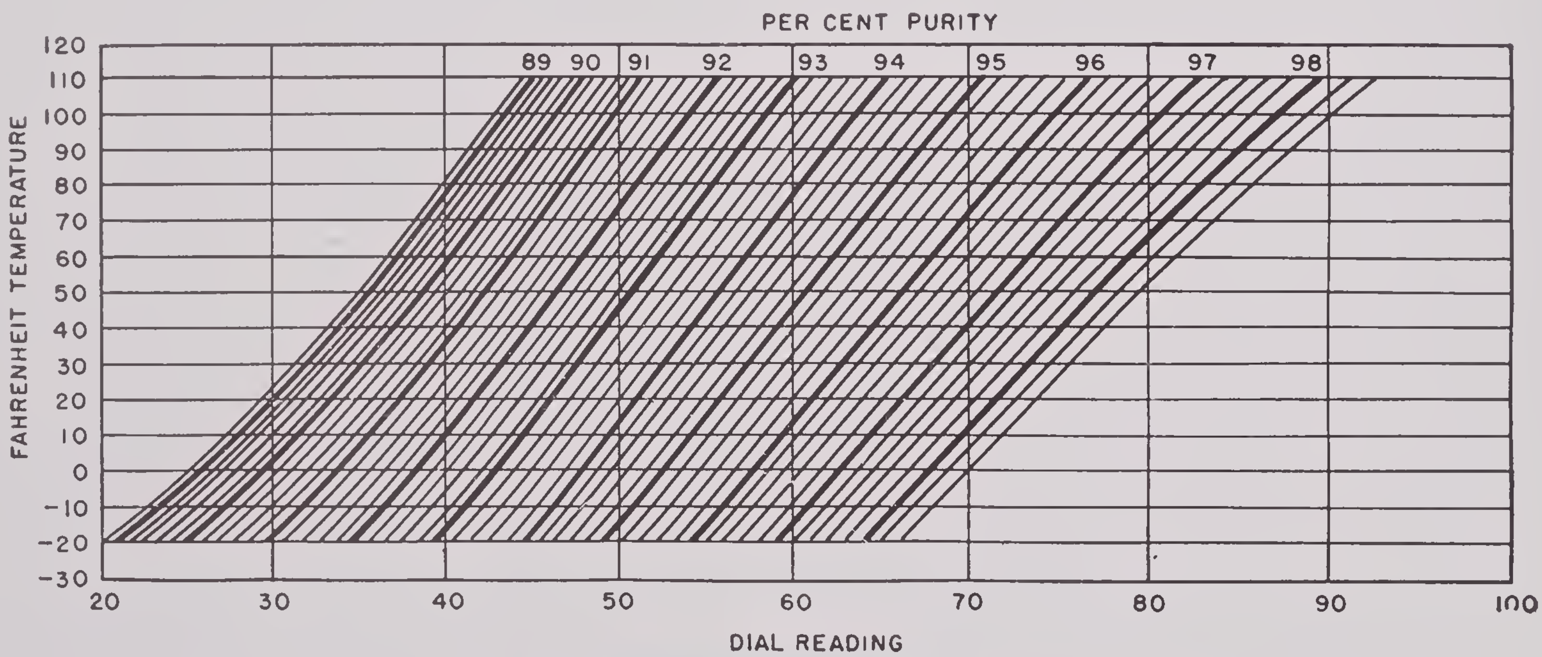

FIGURE 4. Percentage purity of helium as function of dial reading and Fahrenheit temperature.

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tivity had already been used at Lakehurst and hence were not considered further. Methods based on measurement of viscosity, dielectric strength, and specific heat appeared to be inherently inaccurate for various reasons. Methods based on the absorption of sound or light (infrared or ultraviolet) seemed too difficult to be set up in the field. Other methods, based on measurement of density, velocity of sound, rate of diffusion, index of refraction, etc., appeared to be adaptable for precision field work and of these the velocity of sound was chosen as the most promising.

11.3 CHANGE-OF-COLOR INDICATOR [CCI][4]

11.3.1 Introduction

The VSI described above required a relatively large volume of gas for a determination. A device suitable for measuring the purity of small volumes of helium, such as are used in range finders, was also needed. The NDRC was requested to undertake the development of such a device, and the CCI resulted.

11.3.2 Military Requirements

The device was to operate up to about 10 per cent air contamination with an accuracy of about 10 per cent in this figure. An additional requirement was that it be very small—in one application because of space and mechanical limitations, and in another because of weight limitations.

11.3.3 Summary of Development

In studying the problem, a number of gas and contamination indicators were investigated in the trade literature. Many commercial devices used simply a vial or ampule which can be broken, the contents of which change color to indicate the presence of the gas it was designed to detect. A similar scheme was developed by the Gulf Research and Development Company[4] for detecting by chemical means air (actually oxygen) contamination in helium.

The method developed does not actually determine the percentage contamination but rather indicates whether or not the contamination exceeds a specified value. The equipment for such a purity determination consists of a small glass vial, with enclosed liquid, attached to the apparatus to be tested by means of a small rubber hose which can be constricted with a clamp.

11.3.4 Description and Technical Information

The arrangement for a purity determination is shown in Figure 5. The screw clamp is placed loosely at a mark on a small-bore rubber tube, and the sealed tip of the vial is slipped into the long end of the tube up to the bulb's shoulder. Another section of auxiliary rubber tube is attached to the helium-filled apparatus. (The fittings shown in Figure 5 are for a height finder.) The needle valve is then opened, a small quantity of gas is sucked from the apparatus to flush the air out of the valve and the needle valve is quickly closed. The auxiliary rubber tube is removed, and the first section of tube with the bulb attached is connected to the apparatus. The needle valve is opened again, and the tip of the vial is broken inside the rubber tube. Two or three minutes are allowed for the bulb to fill with gas from the apparatus. The rubber tube

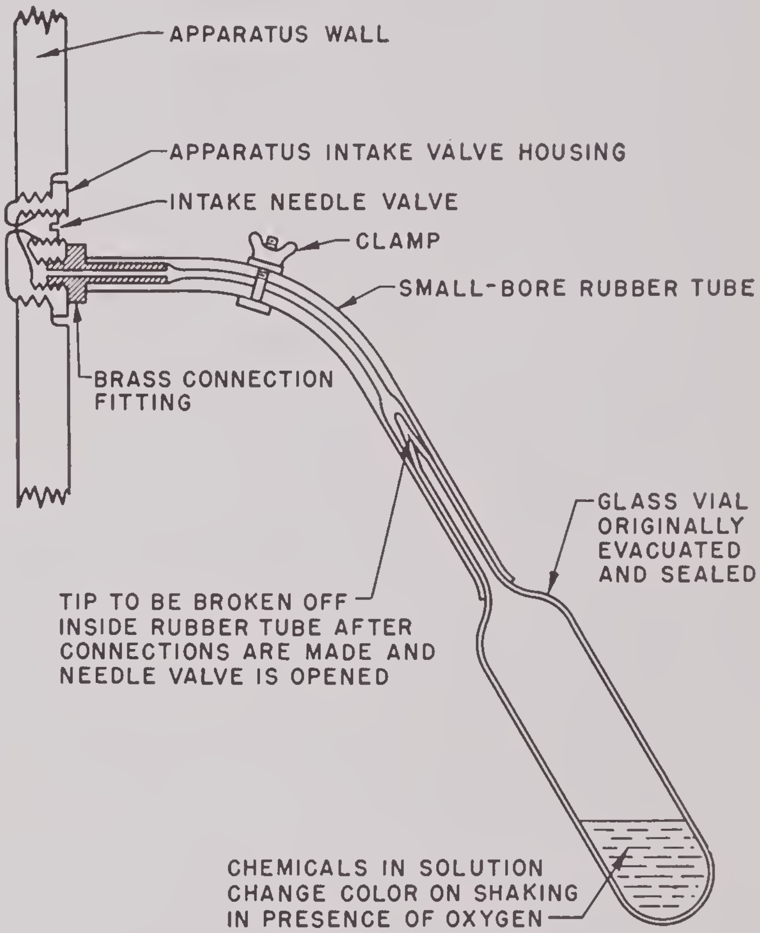


FIGURE 5. Change-of-color indicator assembly prepared for purity test.

is then closed off by means of the screw clamp and the needle valve is closed.

The contents of the vial are agitated for about two minutes. The reddish brown solution in the vial goes through a series of color changes, the final color depending on the amount of air present. With small amounts of air, the solution changes to dark green; with larger amounts, to light green; and when the specified limit is reached the final appearance is milky white. If the limit is exceeded, the final change from light green to white occurs quite sharply.

The vials have been made to indicate nominally 10 per cent air contamination and can be depended on to give an end point at from 9.5 to 10.5 per cent air under ordinary conditions. For other conditions, there can be supplied a table showing the percentage of contamination resulting in milky white color for pressures between 800 and 600 mm Hg and temperatures between —30 and 50 C. The corresponding percentages of contamination vary from 7 to 17.5 per cent.

The indicator solution used is made by adding 5.26 grams of anthraquinone and 1.16 grams of sodium hydrosulfite to a mixture of 250 ml of 95% ethyl alcohol (boiled) and 250 ml of 0.5 normal sodium hydroxide. Air is excluded during the operations by putting the dry powdered materials in a stoppered flask, evacuating the vessel, and then allowing the mixture of alcohol and sodium hydroxide to run into the flask through a separating funnel.

The vials are filled with the proper quantity of solution to indicate 10 per cent air in the helium under normal conditions of temperature and pressure. The solution is adjusted so that no correction is required for the small amount of air present in the rubber connection to the apparatus. The air in each bulb is displaced with butane before the required amount of reagent is put in, after which each vial is evacuated and sealed.

For maximum precision, it is necessary to take into consideration any air which may be allowed to get into the vial during the test. The inclusion of a small amount of air is unavoidable, but the test procedure has been designed so as to keep its volume constant and small; and the necessary adjustment has been made in the solution to compensate for it. In the particular rubber connection with which the vials are used there is a constant volume of 0.34 ml of air admitted.

A number of these vials were made and furnished to the Naval Bureau of Ordnance, the Coast Artillery Board, and the Field Service Maintenance Division of the Army Ordnance Department.

Chapter 12

BATTLE NOISE REPRODUCTION FOR TRAINING AND SCREENING BATTLE PERSONNEL[a]

THE OBJECT of this project was the development and furnishing of one sample of a loudspeaking system of adequate fidelity and volume for reproducing faithfully the noise of naval battle. The contemplated uses of the equipment were: Marine surface training, battle noise conditioning, teaching men to speak up or use prompt visual observance, psychiatric screening and talker training. The development work of the project was carried out by the Western Electric Company. Naval personnel actively cooperated in the making of recordings and Paramount Studios assisted in re-recordings.

The reproductions were to be in the form of sound films. It was originally decided to make three distinct demonstration films: (1) an identification sequence with a commentary explaining the nature of each individual sound being reproduced; (2) a short jungle combat sequence; and (3) an attack on an aircraft carrier. Items (2) and (3) were to be composed mainly of the individual sounds appearing in the identification sequence.

The reproducing system is composed of three major units, each housed in a separate truck. Unit 1, the reproducing truck, contains the film reproducing machines, motor system, all amplifiers, and control facilities. Unit 2, the loudspeaker trailer, is a truck trailer containing the loudspeakers, horn field rectifiers, and cables for connection to the reproducing truck. Unit 3, the power truck, contains a gas-engine-driven generator which supplies 220-v, 3-phase, 60-c power for the entire system. Power cables for connection to the reproducing truck are carried on the reels in the power truck. These three units may be operated in close physical proximity, the only precaution being that the reproducing and power trucks be located behind the loudspeaker array.

The system is designed to provide reproduction from 200-mil push-pull sound-film records, with or without a frequency-modulated control track. It will reproduce disk records of the vertical or lateral type, either 33⅓ or 78 rpm, and, in addition, provision is made for operation of the system from direct microphone pickup.

The frequency-response characteristics of the entire amplifier system are effectively uniform from 50 to 10,000 cycles. The electric output of the system is 2,400 w and the harmonic content at full output is approximately: 17 per cent at 50 c, 12 per cent at 100 c, 6 per cent at intermediate frequencies, increasing again to 10 per cent at frequencies above 7,000 c. For lower outputs, say 800 to 1,000 w the distortion is reduced to about 5 per cent for all frequencies. These distortion components are contributed by the final power amplifier.

The loudspeaker array provides an acoustical response effectively uniform for frequencies from 50 to 7,000 c, and has a usable range from 30 to 10,000 c. Loudspeaker efficiencies of 50 per cent are achieved, and for full system electric output, a sound field of 130 db at 100 ft on axis is realized. The dynamic volume range of the system when operated from sound records on film using control track is 80 db. Approximately 92 per cent of the total sound energy is radiated from the mouths of the loudspeaker array, the remaining 8 per cent being radiated from the rear. In general, the directional radiation of the array is confined to a total angle of 30 degrees. Distribution is complicated by the fact that the array is not a point source, that ground reflection occurs in various ways, depending upon terrain, and that the higher frequencies are attenuated more rapidly in air than are the lower frequencies. In addition, as would be expected, wind has a marked effect upon distribution and sound

[a] Time and personnel were not available for preparation of the usual sort of Summary Technical Report of this work. The material reproduced here is taken essentially verbatim from the contractor's final report. This condensed report is intended to give an idea of the nature of the work and to call attention to the detailed contractor's reports associated with it.

field intensity. Listening tests indicated that the system could be heard over flat desert terrain for 2.5 miles on axis, with slight crosswind when the relative humidity was 10 to 15 per cent.

The technical details of the system are given in the contractor's progress report.[1]

All original recordings were made at a Naval or Marine Corps establishment in the Eleventh Naval District Area. Naval personnel were assigned to assist the recording group in obtaining the particular sounds desired at the various locations. Recordings were made at the Destroyer Base at San Diego, at the Pacific Beach Anti-Aircraft Training Center, at Miramar Landing Strip, at the Marine Camp at Camp Gillespie and at Camp Pendleton.

The actual editing and cutting for re-recording was governed to a large extent by the original film records obtained under actual field recording conditions. All sound tracks to be used in re-recording the final negative were organized, cut for proper timing, etc., before actual re-recording was done.

The aircraft carrier attack needed a very complete sound record. To the normal background sound of sea and wind was added the firing of several types of antiaircraft guns, the sound of approaching planes, individually and in groups, the machine-gun fire of those planes and finally the explosions caused by bombs and torpedoes. The climax of this sequence required the combination of twelve separate sound tracks.

The sequence depicting jungle warfare was composed of much simpler elements. Although the climax demanded the use of nine separate tracks most of the sequence was handled by combining three or four. It was principally the responsibility of timing to make the rifle and machine-gun fire, mortars and grenades sound as though they were being used in combat.

The recording of the above sequences was done at the Paramount Studios.

The equipment was delivered to the Navy in January 1944. It was planned that the system should be used concurrently in connection with two primary programs—the study of the psychological effect of battle noise on personnel and the training of Navy personnel under simulated battle conditions.

In connection with this work it was decided that additional recording should be made. These were made at the Anti-Aircraft Training Center, Dam Neck, Virginia; on the USS *New York* on training cruise; at the Naval Proving Ground, Dahlgren, Virginia; and at the Amphibious Training Base, Coronado Island, San Diego, California. A complete list of the recordings taken is contained in the contractor's report,[2] as well as the details of four thirty-minute battle sequences derived from recordings.

SOUND SPECTRUM OF ORDNANCE EQUIPMENT AND BATTLE NOISES[a]

THIS PROJECT was begun on April 1, 1942, on the recommendation of the General Development Laboratory of the Signal Corps. The objective was to study sounds from ordnance equipment, to obtain information about the frequency composition of sounds originating from various weapons, the intensities of these sounds, the phase relationships of the various components, and any other information about the sounds which might be useful in connection with sound ranging. It was felt that as complete as possible a knowledge of these sounds was essential in order that available sound-ranging equipment might be used to its fullest capabilities and that better apparatus might be designed. The work was performed by Western Electric Company under Army Service Project SC-27.

The study included sounds from machine guns, mortars, and various field-artillery weapons ranging in size from the 105-mm howitzer to the 240-mm howitzer. Under battle conditions noise may interfere with the operation of sound-ranging equipment. Information about the character of interfering sounds is therefore desirable. A complete investigation of all possible interfering noises could not be made, but a partial investigation was made in which the sounds from a number of army vehicles were studied.

The initial interest was in the sound spectra produced by .30- and .50-cal machine guns. High-quality phonograph recording equipment was assembled and taken to Aberdeen Proving Ground where recordings were made of the muzzle waves and ballistic waves from these guns at various distances. The records were subsequently reproduced electrically, and by means of wave filters a determination was made of the frequency spectra of the sounds.[1]

Although the recording system used for the machine-gun tests was the best available at the time the response was limited on the low-frequency end to 40 c. Later, when it was requested that larger-caliber guns be investigated it was realized that the original recording system would be inadequate. A recording system was therefore developed which had a very wide frequency-response range, uniform from 0.1 c to several thousand cycles per second. This system was practically free from amplitude and phase distortion over its operating range.

With this system recordings were made of various guns and howitzers at Fort Bragg through the cooperation of the Field Artillery Board. Field-artillery weapons ranging in caliber from the 105-mm howitzer to the 240-mm howitzer were studied. Additional tests of machine guns were also made. The results of these various tests were given in the contractor's final report.[4]

With this same recording system studies were made of the sounds from 60-mm, 81-mm, and 4.2-in. mortars at various distances up to 2,000 yd. The results of this study[3] showed why sound ranging on light mortars is difficult. At distances at which sound ranging is customarily conducted the intensity of the sound from the 60-mm mortar was found to be about the same as that of the ambient noise. The energy in the mortar sounds is concentrated at a higher frequency than for the field-artillery weapons and lower than for the machine guns.

A study was made[2] of noises from a number of typical Army vehicles ranging in size from the jeep to an 8-ton truck and including some tractors.

The reports in the bibliography constitute a complete record of the studies conducted under this project. The following is an abstract of the final report.

1. A recording system was developed having the exacting performance characteristics needed to record faithfully the sounds from various field-artillery weapons. With this system almost 500 records were made at Fort Bragg. Analyses

[a] Time and personnel were not available for preparation of the usual sort of Summary Technical Report of this work. The material reproduced here is taken essentially verbatim from the contractor's final report. This condensed report is intended to give an idea of the nature of the work and to call attention to the detailed contractor's reports associated with it.

of 110 selected typical records were made with an Henrici analyzer. The complete results are given in OSRD 4594.[4] To supplement these analyses about 300 of the original oscillograms are appended.

2. The analyses of the spectra of muzzle waves from weapons of large caliber (105 mm to 240 mm) show that at distances of interest in sound ranging, the major part of the energy lies in the frequency range from about 2 to 40 c.

3. The ballistic wave, originating at the projectile in flight, has a sound spectrum which can be readily differentiated from spectra of sounds originating in other ways. The analyses of the ballistic waves do not always show that the maximum energy is concentrated within a limited region. When the major energy *is* so concentrated, the region is located much higher in frequency than for the muzzle wave originating at the gun. Sometimes the maximum energy is at about 100 c.

4. The spectrum of the sound produced by the explosion of a shell is similar to that of a muzzle wave from a large-caliber weapon. On visual inspection of the oscillograms, however, high-frequency wavelets are evident, preceding the main wave caused by the explosion of the shell. These oscillograms are therefore readily identified as being shell sounds.

5. The "frequency" of the region of major energy for the muzzle waves is influenced at the source by such factors as the weight of the charge of powder used to propel the shell and the dimensions of the gun, and is affected in its propagation by the distance and the terrain between the gun and the microphone.

6. Additional data on machine-gun sounds confirm earlier findings.[1] The better performance characteristic of the recording system used in the later tests confirmed the presence of the low-frequency energy, as suspected, and showed its magnitude.

Chapter 14

D3 PROJECTS REPORTED BY DIVISION 17

By *J. S. Coleman* [a]

14.1 INTRODUCTION

CERTAIN OF THE PROJECTS completed under Section D3 of the NDRC prior to the organization of Division 17 were of such nature that had Division 17 been in existence at the time of their inception they would have been assigned to it. References to these projects were made in the initial Bi-Monthly Summaries of Division 17. Since these projects will not be reported elsewhere, résumés of them are included in the Division 17 Summary Technical Report. In connection with each, reference is made to a detailed bibliography. The work on all these subjects was conducted during 1941 and 1942; and these brief reports are written to indicate the status of each at the end of 1942.

14.2 THERMISTORS

The term "thermistor" is a contraction of the words "thermal resistor," and describes a new type of circuit element whose resistance varies markedly with temperature. Three classes of thermistors are used in electric circuits—the externally heated units, the indirectly heated, and the directly heated. The first of these is a simple thermistor which is usually made in the form of a bead, disk, rod, or strip whose resistance is caused to vary by changes in ambient temperature. This type finds application in the measurement or control of temperature, the detection and measurement of radiant energy or as a temperature-compensating device in electric circuits. The second, or indirectly heated type, consists of a thermistor unit in thermal contact with a heating coil. By controlling the power supplied to this coil, the thermistor resistance can be made to vary over a wide range. This type finds use as an indirectly or remotely controlled circuit element in telemetric or automatic-control functions. The third type of thermistor is directly heated by the power dissipated in it by the current flowing through it. Because the thermistor materials have large negative temperature coefficients of resistance, a unit of this last type has the property of "negative resistance." If the current through such a unit be increased beyond an initial critical value, the voltage across the unit will decrease with increasing current. This phenomenon is due to the rapid decrease in resistance resulting from the power dissipated as heat in the unit.

It was, perhaps, the directly heated variety of thermistor which provoked the greatest interest. Along with their property of dynamic negative resistance, units of this type have the additional property of inductance, due to the lag introduced in the electric response while the unit reaches thermal equilibrium. Thus the static-response curve may differ radically from the dynamic characteristic as the thermal lag prevents the effective temperature from following rapid changes in current, so that at high frequencies the thermistor behaves as an ohmic resistance whose value is determined by the total dissipated power. Higher response speeds may be obtained by reducing the thermal capacity and increasing the rate of thermal loss. The limitation in speed of response and the dependence on ambient temperature proved the principal difficulties in the course of this project.

A number of specialized uses for thermistor devices had been discovered and applied by German and American laboratories and an even greater number had been suggested by the unique thermistor properties. It was in order to investigate the feasibility of some of these suggestions and to determine the conditions of operation under which they might be profitably employed that a thermistor program was started shortly after the formation of the NDRC in 1940. As a result of these studies it was decided that for the applications investigated, with one or two exceptions, the thermistor in its existing form could not be considered satisfactory for service under military conditions, as operation is generally critical with ambient temperature

[a] Assistant Director, Summary Reports Group.

unless the device is thermostated or otherwise compensated. The applications included the use of a thermistor as an amplifier, tuned filter, sine-wave oscillator, precise time delay, means for self-balance of bridge circuits, current relays, and fluid-flow meters. Unless the device is itself used to measure, or is controlled by temperature, it must be compensated, either electrically or thermally, for stable precise operation. Unfortunately in these cases this compensation was either inconvenient or not possible to accomplish.

It is not implied that thermistors are unsatisfactory for all applications under these conditions of wide variation of temperature. Many functions are being well served by their use. These functions, however, being simpler and better suited to utilize the characteristics of the thermistor, were established and, in many cases, practiced prior to this program. Such functions include current and voltage regulators, surge and transient discriminators, remotely controlled resistance units, resistance-capacity oscillators, and many others. This NDRC project, in addition to defining and extending the conditions of use for these functions, developed the additional functions of telemetric temperature indicators and sensitive bolometer or radiometer elements.

The former of these two provided a simple reliable means for the measurement of temperature at some remote spot. Suggested applications were temperature indicators for aircraft cylinder heads, temperature-controlled modulators for radio-sounding meteorological balloons, clinical thermometers, oil-temperature indicators, and others. Scales can be adjusted to give any degree of accuracy over any temperature range up to several hundred degrees centigrade. The second of these developments, that of the bolometer, has already made remarkable contributions in the field of detection and measurement of infrared radiation. By means of the sensitive thermistor as a detecting unit it has been possible to more than double the sensitivity and speed of response previously possible with metal-strip bolometers. Although this development is described more fully in the Division 16 Summary Technical Report,[50] it is of interest to note that a sensitivity of 10^{-9} w of incident radiation over the band 5 to 20 microns has been obtained with a response speed of better than 10^{-2} second. This is of real importance not only to military problems of detection and communication but also to the wide field of infrared spectrometry, vital in the analysis and control of synthetic rubber manufacture and other war-industry products and processes.

By the time of the entry of the United States into the war, the more urgent need for work of other nature resulted in the abandonment of all of the thermistor-circuit investigations. Although it is possible that further effort might have expanded their fields of use, it is believed that other projects, promising more immediate and vital returns, justified the diversion of effort. When it is again possible to take up the problems of thermistors, it is anticipated that their use will be widely expanded. The development of a mechanically stable, thermostated, high-speed thermistor, capable of dynamic operation over the audio-frequency range, will make possible the design of extremely high-Q filters with great savings in size, weight, and cost. It is probable that new designs, incorporating grid connections for local heating, and giving amplifier action without expenditure of filament power, will be devised, along with many other novel and specialized forms. It is particularly recommended that the engineering branches of the Air Services, with their severe problems of temperature compensation of instruments, take every opportunity to benefit from the use of thermistors.

The work on thermistors was conducted under a number of project headings and by a variety of contractors, as follows:

Thermistors
- Carnegie Institute of Technology[1,2]
- Massachusetts Institute of Technology[20,21]
- Rensselaer Polytechnic Institute[33,34]
- Yale University[46-48]

High-Speed Thermistors—Harvard University[12-14]

Thermistors in Connection with Temperature Control—University of Minnesota[42-43]

Methods of Compensating Thermistors and Thermistor Circuits for Ambient Temperature Variations—University of Minnesota[44-45]

Applications of Thermistor Units for Applications Designed by the Chairman of Section D3[b]—Harvard University[15-19]

Thermistors as Trigger Amplifiers—The Franklin Institute[3-5,49]

Thermistor Bolometer—Northwestern University[31,32]

Application of Thermistors to Submarine Mines—Princeton University.

14.3 DEVELOPMENT OF TELEMETRIC FLOWMETERS

The development of a thermistor flowmeter was briefly mentioned in Section 14.2. A flowmeter is important for the operation of long-range aircraft in that it provides an instantaneous check on the rate of consumption of fuel. At the time that this project was begun, there was no available aircraft flowmeter which could combine the required accuracy with reasonable specifications of reliability, size, and power consumption. The thermistor, having an extremely high temperature coefficient of resistance, held some promise as a Pirani-gauge type of flowmeter. Therefore, an attempt was made by the Gulf Research and Development Company,[6-10] to design a thermistor flowmeter which would not only indicate rates of flow between 30 and 300 gallons per hour with an accuracy of ±3 per cent but would also provide this accuracy over the temperature range of at least —20 to +30 C. Considerable effort was expended on this program before it was finally decided that, while the thermistor unit had adequate sensitivity, it was not feasible to secure the necessary accuracy over the wide ranges of temperature required by operational specifications.

The contractor next turned to the most promising commercial development in flowmeters with the idea of improving its perfomance to meet the specifications set by military requirements. The unit selected[11] was a rotor-type flowmeter comprising a screw or spiral-bladed rotor revolving concentrically in a cylindrical nonmagnetic-steel measuring section whose inside diameter was approximately that of the flow line in which it was to be inserted. The rotor, slightly over 1 in. in diameter, was free to rotate on ball bearings about the axis of the flow line with small clearance between the rotor and the measuring section. Integral with the rotor was a small magnet with its poles displaced from the axis of rotation. A pickup coil and magnetic circuit were arranged opposite the rotor and outside the measuring section in such a way that an a-c generator was formed. The output of this generator varied in frequency and voltage with the speed of rotation of the rotor and consequently with the rate of fluid flow. The indicating element which received the a-c output from the metering element was a 270-degree-scale rectifying milliammeter normally mounted on a panel at a distance from the generator. This device in laboratory tests could be adjusted to give an accuracy of ±3 per cent for a single temperature condition, and approximately ±8 per cent for the temperature ranges required. It was found that these errors were due to three factors: (1) a change in generator output with temperature, resulting from the change in permeability of the rotor magnet and the stator-field materials; (2) the increased slippage of the rotor with increased rates of fluid flow, and the thermal expansion of the fuel; (3) the change in calibration of the indicator instrument with temperature. Each of these factors contributed an additive error of between 2 and 3 per cent, indicating values lower than actual with increasing temperature.

It was found possible to decrease two of these errors by introducing straight flow-line connections into and leading from the metering rotor and by the development of a frequency-indicating meter which was not temperature sensitive. Further, it was learned that much of the slippage error due to the expansion of the fuel with increased temperature could be reduced if mass rate of flow rather than volume flow (giving fuel consumption in pounds rather than gallons) were considered. Recommendations based upon these experimental findings were turned over to the commercial manufacturer and military agencies. Best results obtained with this corrected commercial instrument showed that a mass-rate-of-flow accuracy of ±2 per cent over a temperature range of

[b] AC-34.

—20 to +110 F could be realized. Further, this gain was accomplished without requiring additional size, weight or power consumption. With specifications met, this project was terminated in August 1942.

14.4 STRAIN GAUGES[c]

Following expressions of interest on the part of Army and Navy aircraft-testing sections, a program leading toward the development of improved wire strain gauges was instituted in January 1941 under contract with the University of Pennsylvania.[35-41] At that time three types of gauges were used for measuring structural strains—magnetic reluctance, optical lever and resistance wire strain. None of these was completely satisfactory. While the magnetic gauges possessed the advantage of large output without amplification, they were undesirable with regard to linearity, temperature compensation and difficulty of mounting. The optical gauges, having adequate sensitivity, were difficult to mount, lacked temperature compensation for some applications, gave results which were not generally reproducible, and were almost impossible to telemeter. Existing designs of wire gauges were principally criticized on the basis of lack of temperature compensation, low output, impossibility of recovery after measurement for recalibration, expendability, and high cost.

On the basis of these and other criticisms of existing designs a set of specifications was prepared by the Matériel Division, Wright Field, USAAF, to cover the design of an ideal wire gauge. These specifications were:

1. The gauge should reproducibly record strain up to ± 0.5 per cent, with a precision of 1 per cent of the maximum strain.
2. The gauge should be linear over the range of strain to be recorded.
3. The calibration constant of the gauges should be independent of temperature from —40 to 140 F. Strains resulting from thermal expansion of the member under test should not be recorded.
4. The gauge should be less than 1.5x0.5x0.75 in. in size and should weigh less than 1 oz.
5. The power consumed by the gauge should be less than 50 mw.
6. The output of the gauge for a strain of 0.5 per cent without auxiliary amplification, other than that obtained with an output transformer matched to an impedance of 0.5 megohm, should be not less than 5 v.
7. The gauge should be demountable in less than 15 minutes for the purpose of rechecking the calibration and should be remountable in a corresponding length of time.
8. The attachment of the gauge should not damage the surface to which the latter adheres, should not affect the material of which the test member is made, nor alter appreciably its mechanical impedance.

The first step in the design of a resistance wire gauge to meet these specifications was the development of a temperature-compensated gauge. This was achieved by using four similar resistance-wire arms in a Wheatstone bridge arrangement. Two diagonally opposite arms are cemented to the surface to be studied while the remaining two are cemented to a strip of the same material which is not strained but is placed in juxtaposition with the surface in question, so that the temperature of all arms is the same and the effect of any thermal expansion of the member is nil. The advantage of this arrangement is that not only is the output twice that of one arm alone, but also the bridge connection minimizes the effect of lead resistance and permits the use of long lines. In order to minimize errors resulting from flexure and to insure intimacy of contact and ease of application, the gauges are made by cementing the wire elements to a paper strip which is applied directly to the surface to be measured with a quick-drying adhesive.

A number of designs involving various arrangements of bridge arms, papers, and glues were made before a satisfactory design was reached. This design, while admittedly a compromise, was given extensive tests which corroborated its laboratory performances. Two models were made—a small unit having the compensating arms located above the strain arms and a larger standard unit having the compensating arms located alongside the strain arms. As expected, this latter arrangement

[c] AC-20.

gives a more exact compensation for temperature. The physical specifications of the units are:

1. *Dimensions.*

Size	Standard	Small
Length	1.5 in.	1.3 in.
Width	0.8 in.	0.3 in.
Height	0.25 in.	0.2 in.
Total weight	0.14 oz	0.1 oz
Effective area	0.9x0.6 in.	0.9x0.2 in.
Distance from test member to gauge	0.003 in.	0.003 in.

2. *Electric constants.* Each arm of the gauge consists of 5½ in. of 1-mil lacquered constantant (advance) wire laid in six zigzags about ⅞ in. long, with 1⁄32-in. separation, giving an arm (and bridge) resistance of approximately 140 ohms. (See Figure 1 of D3 174.[39]) With 45 mw of power furnished each bridge unit from a stabilized 2,000-c oscillator, 10^{-5} v is obtained for a strain of 10^{-5}. An a-c amplifier raises this level to that necessary to drive a rectifier-meter indicator giving full-scale deflection (100 divisions) for a strain of 70×10^{-5}.

3. *Linearity.* The gauges themselves are linear and reproducible to better than $\pm 5 \times 10^{-5}$ strain (i.e., 1 per cent of 0.5 per cent strain). The linearity of the oscillator and amplifier are designed to be below this figure.

4. *Range.* A maximum range of $\pm 10^{-2}$ strain (i.e., 1 per cent strain) is possible at frequencies up to at least 30,000 c. There are no detectable humidity or corrosion effects (except as they affect the time required for the fixing glue to set).

5. *Temperature effects.* For different positions of the dummy arms, these are shown in an unnumbered illustration in D3 284.[41] For the standard gauge, these all reduced approximately $\pm 10^{-5}$ strain from —10 to over 120 F. Adding 150-ft leads approximately doubles this error.

6. *Tension or compression.* It is possible to differentiate between compression and tension by a phase-sensitive device such as the magic-eye tube.

7. *Error due to stiffness of gauge unit.* For a force of 1 lb, this has been measured to be equal to a strain of 3×10^{-4} for the standard unit and 9×10^{-4} for the small. This corresponds to errors of 1.5 per cent and 0.75 per cent, respectively, if the units are used on 1⁄32-in. duralumin. This error decreases with increasing thickness of the test member.

8. *Attaching gauge to member.* This has been done by using ordinary synthetic adhesives (such as Duco cement) diluted with volatile solvents. With these, a drying time of 4 to 20 hours is required, depending upon the humidity and magnitude and duration of strain.

9. *Recalibration of gauges.* The units can be removed, for recalibration after a series of measurements, by softening the bond with a solvent and using a razor blade to detach the paper from the test member. However, in view of the uniformity with which these units are manufactured, this process is believed unnecessary and is not recommended.

10. *Effect of long leads for telemetering.* The balance of the bridge is not affected by lead length provided noise pickup does not occur at oscillator frequency. However, there is a slight temperature effect.

11. *Errors arising from flexure.* These gauges, in common with most gauges, do not distinguish flexure from pure strains. The error is a function of the distance of the gauge element from the member, and is minimized in the case of these units by having the elements only 0.003 in. from the test surface. This error can be eliminated by putting a gauge on each side of the test member, in which case the pure strain is given by the sum of the readings and the flexure by the difference.

12. *Installation and operation.* A section of the circuit of an equipment constructed for testing of aircraft structures is shown in an unnumbered illustration in D3 284.[41]

It is believed that these refinements, although not representing the ultimate in the design of wire strain gauges, have made it possible to extend the use of such gauges under a wide variety of conditions in laboratory structures for testing and proving. Being small and compact, inexpensive to manufacture, easy to attach, insensitive to temperature variations, and allowing long lines which permit telemetering, rapid switching from unit to unit, and the application of standard amplifier and indicator techniques, they represent a flexible and valuable contribution to the art. Although Section D3 recognized that much remained to be done

in the way of developing quicker setting cements and simplified mechanical designs, it was felt that these improvements might more logically be accomplished by the several laboratories and the manufacturer. Consequently, after the results of this project were communicated to the interested military establishments, the project was terminated.

14.5 MEASUREMENTS OF STRAIN TRANSIENTS ON EXTERNAL SURFACES OF GUN BARRELS[d]

Paralleling the project on the improvement of strain gauges, Section D3 was requested by Watertown Arsenal to cooperate in a program leading to improved methods of simultaneous high-speed measurements of strains experienced by gun barrels during firing. It was believed that the accurate and complete determination of the magnitude, period, and location of these strains would permit improvement in gun design and manufacturing processes, leading in turn to longer barrel life, higher muzzle velocity, and increased production. The NDRC project in this case was charged with the development of suitable measuring apparatus and with assisting in making and interpreting the first series of measurements on a sample barrel. It was not concerned with the collection of data or interpreting its significance as it might affect design or production, this being held the proper function of the arsenal technical staff.

A program was set up calling for the design and construction of a complete laboratory equipment capable of simultaneous multiple recording of high-speed strain transients having minimum periods of 5×10^{-5} second. The equipment, as developed, utilized electric wire-type strain gauges (not compensated for temperature) to produce voltages proportional to the strains observed by unbalance in a bridge circuit. These voltages, after passing through bridging and selector circuits, were fed into the vertical amplifier of an oscillograph where they controlled the deflection of the spot on a short-persistence, blue-screen, cathode-ray tube. An oscillographic trace was obtained by photographing the vertical position of the spot on high-speed film attached to the periphery of a moving drum which rotated about a vertical axis. A square-wave electronic switch was provided to bring the spot into the camera field during the measurement period. Four such camera oscilloscopes were provided in the complete equipment, permitting simultaneous recording (through a simple switching arrangement) of 4 of 32 attached gauges. A time reference was obtained, by a momentary electric contact, established by the projectile between the barrel and a taut wire stretched in front of the muzzle, which gave a sharp deflection to one of the oscilloscope traces. Means were also provided for individual calibration for each of the several gauges.

With this system, it was found possible to record strains of the order of 2×10^{-6} in. per inch having periods as short as 5×10^{-5} second. It was also possible for the first time to study the effects of recoil, the expansion and contraction of barrels resulting from gas pressures and driving band motion, and the ovalizing and vibratory strains, both in tension and torsion. The first series of measurements, made on a 37-mm field gun, yielded much valuable information. It showed, for example, that the maximum strains resulted from the passage of the driving band. This strain takes the form of a barrel expansion at the point of the driving band, immediately preceded and followed by a compression, as well as a rather severe and complex vibratory condition, starting at the muzzle with the emergence of the projectile. Very little ovalizing deformation was observed. For a complete report of these measurements see D3 287.[26]

During the course of this project there was developed an additional piece of equipment for the measurement of internal diameters of barrels under very high hydrostatic pressures. This device—an electric micrometer—is based on the principle of a wire voltage divider, the position of the slider on the resistance wire being controlled directly by the internal dimension of the barrel. The voltage divider is connected in a Wheatstone-bridge circuit, the resistance wire serving as two adjacent arms of the bridge with the slider as one of the bal-

[d] AC-20.

ancing contacts. This device gives 0.001-in. accuracy for water or oil immersion temperatures of 20 to 60 C, and with pressures exceeding 10^5 psi.

After the first measurements with this equipment arrangements were made to turn it over to the arsenal laboratory to be incorporated into a special laboratory constructed for the purpose of continuing measurements on the 37-mm and other barrels as well as various designs of mounts and carriages.

14.6 THE RADON INDICATOR

One of the serious problems that has confronted industrial health authorities for a number of years is that of radium poisoning of personnel handling radioactive luminous paint. As there is no known cure for serious cases resulting from overexposure to these compounds, it is of paramount importance to prevent such overexposure. To do this it is necessary to have an instrument which has adequate sensitivity to detect the presence of tolerance quantities of radon in the breath samples of exposed workers. Although such instruments were available prior to the inception of this project, they were judged unsuitable because their low sensitivity and the excessive time required to make a single analysis precluded the possibility of maintaining adequate control of worker exposure and poisoning.

An instrument capable of measuring the amount of radon present in an air or breath sample serves the double purpose of measuring the amount of radium and its decay product present in a human body, and measuring the amount of radon in room air which may be harmful to the shop workers. That such an instrument is both necessary and adequate to the control of worker radium poisoning is firmly established, for the best index of the total amount of radium stored in the body of a victim is the radon content in the expired breath. Medical research has determined that the tolerance dosage of radium has been reached, when a breath sample from an exposed person contains 10^{-11} curie of radon per liter of air. The measurement of these concentrations is accomplished by counting the α particle activity of the sample. Hence, the problem undertaken in this project by the Massachusetts Institute of Technology[28-30] was to develop a practical apparatus capable of counting 150 α particles per hour (10^{-11} curie) from radon and its decay products to an accuracy of 20 per cent in a reasonable period of time.

The problem was broken down into three parts: (1) the design of a rugged sampling flask by means of which breath samples and room-air samples might be conveniently obtained, (2) the design of a suitable α-particle detecting apparatus, and (3) the design of a suitable indicating and/or recording equipment.

The detecting and indicating apparatus developed consists, essentially, of a sensitive ionization chamber which feeds pulses into a high-gain linear amplifier whose output operates an Esterline-Angus pen recorder. The passage of an α particle in the ionization chamber is recorded as a deflection of the pen recorder, thus yielding a permanent record of the event. The final apparatus constructed was capable of measuring 10^{-12} curie of radon in the first two hours to an accuracy of 20 per cent. It was therefore more sensitive by a factor of 10 than called for in the original specifications. This additional sensitivity proved of great benefit in maintaining rigid control over workers during the early periods of exposure. The counting range of the apparatus is approximately 50 to 500 α particles for a two-hour run.

The complete apparatus, being highly sensitive, requires shock-proof mounting and operation by a skilled technician. In view of this and in order to make radon-analysis service as flexible and widely available as possible, two types of special sampling flasks were developed—one for obtaining samples of breath from patients, and the second for obtaining samples of air from rooms suspected of containing radon. The breath-sampling flask consisted of a one-liter, pyrex flask with a specially designed two-way stop-cock. The device was so arranged that when a blowing tube was protruding up from the flask, air from the lungs could be blown through the flask; and when the blowing tube was turned down, the flask was sealed from outside air. The sampling flask, designed to collect room-air samples, consisted of a

1-liter glass flask with two stop-cocks. This type of flask may be evacuated and opened at a point where the atmosphere is suspected of containing measurable amounts of radon.

For convenience in shipping and handling, the flasks are contained in specially developed 2-gallon metal cans filled with shock-absorbing material having the consistency of hard sponge rubber. Rigorous shock and sustained-pressure tests have proved the ruggedness of this design. By the use of a large number of these flasks, a single detecting and indicating apparatus is able to provide quick and reliable service to a large number of plants and factories. As of early 1945, three sets of equipment had been constructed for this service, which was widely used by military medical services, insurance companies, state industrial hygiene departments and federal health agencies.

With the design, construction, and successful demonstration of this equipment, Section D3 made arrangements for the unit to be taken over by a nonprofit laboratory to provide this service at a minimum of time and cost to all individual companies and agencies requiring it.

GLOSSARY

AFC. Automatic frequency control.

α Particle. Helium nucleus.

Aperiodic FEI System. A firing error indicator system in which the microphone or microphones are highly damped, have a frequency flat response characteristic up to about 10,000 c and are used to reproduce with a high degree of fidelity the wave-form profile of acoustic shock waves. For other characteristics, see text (Sections 2.5.2, 2.5.3, and 2.6.7).

Aperiodic Microphone. *See* Aperiodic FEI System.

Apex Angle (of shock-wave cone). The shock-wave disturbance trailing backward from the nose of the bullet has the shape of a right circular cone with the trajectory as axis of symmetry. The angle a made by any element of this cone with the axis is called the apex angle (sometimes called the semi-apex angle). This angle is given by $\sin a = s/v$ where s is the velocity of sound and v the velocity of the bullet. Since the H and T discontinuities have velocities respectively slightly higher and slightly lower than sonic, the shock-wave cone referred to is in strictness to be regarded as lying somewhere (about midway) between these two boundaries. It defines the position of the intermediate point of zero amplitude in the N-wave profile where the velocity is sonic.

Arrival. Initial record of a seismic wave on a seismograph recording, usually an abrupt change in form of recording line.

Aspect Angle. The angle between the target plane and the common axis of the two microphones in an FEI transmitter, or the complement of the angle between the direction of the bullet trajectories near the FEI transmitter and the microphone axis.

Aspect Angle Errors. Deviations either of sum or of difference response which come from orientations of the microphone axis oblique to the target plane; that is to say, for aspect angles different from zero.

AVC. Automatic volume control.

Binary Counter. A simple electric counter consisting of two tubes which are made alternately conducting by successive impulses.

Block I, Block III. Army-Navy identification of airborne television apparatus developed by Radio Corporation of America, Camden, New Jersey.

CCI. An HPI based on change of color of a liquid.

Channel (receiver channel). In the aperiodic FEI system, the shock-wave signals from each of the two microphones in the transmitter are separately transmitted at different radio carrier frequencies to the receiver where they are separately received in two different and distinct channels. The microphone signals remain in separate channels of the receiver up to the "sum tube."

Commutation System. The scanning of a number of channels to reduce them to one electric channel for radio transmission.

Condenser Microphone. A microphone in which a metal diaphragm forms one of the electrodes of an electric condenser, the other (stationary) electrode being situated close to the back surface of this diaphragm. Minute diaphragm vibrations change the capacity of this condenser by changing the air-gap spacing between these electrodes.

CR. Check remover.

Curie. A unit quantity of radium emanation or radon, defined as that quantity which is in equilibrium with 1 g Ra_3. Its volume at NTP is about 0.63 mm.

Decimal Counter. An electronic counter system for reporting in powers of ten.

Delay Error. The error in miss indication coming from the fact that the shock wave reaches the FEI microphone at a later time than the instant when the bullet pierces the target plane and that, in consequence, the target will have moved to a new position.

Density Pattern (of shots). *See* Normal or Gaussian Shot Density Pattern.

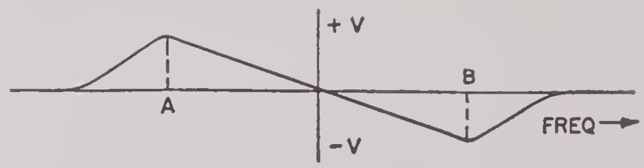
Difference Lobes. The regions of the FEI acoustic pattern in the target plane inside of which the incidence of a shot causes the FEI to report the directionality of a miss.

Difference Response. The difference response or directionality response in the definitive Model XI-A, FEI receiver is a signal appearing in that channel of the receiver corresponding to the one of the two microphones which receives the shock-wave signal first; it is proportional to the signal from that microphone alone.

Difference-Response Lobes. *See* Lobes.

Directionality (of miss). One of the functions of the FEI is to indicate the directionality of a miss, i.e., whether the miss passed fore or aft of the moving (towed) transmitter.

Discriminator. An element of an f-m receiver which, over a limited range of input carrier frequencies, supplies a voltage V proportional in magnitude and sign to the deviation of the input frequency from a standard value. The characteristic, relating input frequency to output voltage, has the indicated shape. The frequency range A to B is the linear working range.



Doppler Effect (in acoustics). A change in the apparent period of an acoustic wave because of the motion of either the observer or the sound source relative to the medium.

ECD. Electronic counter communication device.

EG. High-speed counter auxiliary 1-megacycle electronic gate.

Electronic Counter. An instrument which measures and records the number of electric pulses it receives from a suitably designed network.

Electrostatic (Microphone) Tester. A device which permits oscillographic study of the relationship (in both amplitude and phase) between an input electrostatic driving force applied to a condenser microphone and the resulting instantaneous displacement of the microphone diaphragm. With it the natural frequency of a highly damped diaphragm is determined as the frequency at which input force and displacement are in quadrature. Curves of response as functions of driving frequency can also be obtained with this device.

EMU. Electromagnetic deflection unit.

ER. Electroplated ribbon.

ERT. Electron ratchet tube.

FEC (Firing Error Camera). A camera utilizing the shock-wave signal from the FEI receiver to indicate by a photographic mark on the edge of motion picture film the instant when the shock wave from each bullet reaches the FEI transmitter in the target. The target and the tracer bullet are photographed on successive picture frames of the film so that measurements of these with appropriate correction of the delay of the shock wave signal furnish data as to the magnitude of the miss for validation tests of the FEI in towed flight.

FEI. Firing error indicator.

FEO. Firing error oscillograph.

Firing Test, Static. *See* Static Firing Test.

Flag Target. An airborne towed target which, for use with the FEI, must be made of plastic cloth in the shape of a banner or pennant. Velon is the usual plastic material.

Gamma Ray. Electromagnetic radiation of very short wave length (of the order of 10^{-8} mm) and of nuclear origin.

Gauss, Law of. *See* Normal or Gaussian Shot Density Pattern.

Geophone. A device for detecting or listening to sounds transmitted through the ground.

Half-Life. Time required for the activity of a radioactive substance to decrease to half its initial value.

Harmonic Mean Miss Distance. A gunner's average miss distance determined by classifying his shots into radial miss-distance zones, dividing the number of shots in each zone by the mean radius of that zone, summing all these quotients, and dividing this sum by the total number of shots considered. The reciprocal of this result is the harmonic mean miss distance.

HPI. Helium-purity indicator.

HSDA. High-speed decimal accumulator.

Hydrophone. An instrument for detecting or listening to sounds transmitted through the water.

IF. Internal flux.

Informing (function of the FEI). Continuously and immediately informing the gunner (or anyone else desired) of the *qualitative* nature of the errors of fire at the time they occur. It is distinguished from the *scoring* function which involves *quantitative* statistics regarding a large number of shots as to the radial miss-distance zones in which they fall.

Limiter. A component used in f-m receivers to hold at a constant value the amplitude of the f-m signals. It consists of an r-f amplifier whose output-signal amplitude is independent of the input-signal amplitude, provided the latter stays above a certain critical (or "saturation") voltage. Below saturation the limiter does not perform its function.

Lobes (difference-response lobes or directionality lobes). Regions of the target plane on either side of the FEI transmitter such that the placement of a shot within one or the other will be registered in one or the other directional channel of the FEI receiver.

LU. Light unit.

Master Oscillator Power Amplifier (radio transmitter). This type of transmitter as used in the FEI system consists of a highly shielded frequency-determining oscillator whose tank capacity in part consists of the condenser microphone, so that it is frequency modulated by vibrations of the diaphragm. A separate component, the power amplifier, furnishes power to the antenna (at the frequency controlled unilaterally by the master oscillator) so as to exert negligible reaction on the oscillator from changes in its load such as variations in antenna capacity, etc.

Microphone Axis. In the aperiodic FEI, the axis through the centers of the two microphones, passing diametrically through the spherical transmitter.

Miss Distance, Apparent. The distance from bullet trajectory to FEI transmitter at the instant when the latter receives the shock wave.

Miss Distance, True. The distance measured from FEI transmitter to bullet at the instant when the bullet is in the target plane.

MOPA. *See* Master Oscillator Power Amplifier.

MRM. Magnetic recording media.

MTR. Magnetic transient recorder.

$\mu\beta$. Feedback factor.

Nitrostarch Equivalent. Amount of nitrostarch which must be exploded at point of impact to give same arrival magnitude (as bomb impact does) at detector.

Normal or Gaussian Shot Density Pattern. The so-called law of Gauss for the distribution of shots aimed at a central point of a target. The simplest case is the one having circular symmetry in which the fraction of all shots placed in a zone between the radii r and $r + dr$ is $P(r)dr$, where

$$P(r)dr = \frac{r}{R^2} e^{-\frac{r^2}{2R^2}} dr.$$

In this law, R is called the gunner's "most probable miss distance." According to this law the number S of shots placed inside radius r is:

$$S(r) = 1 - e^{-\frac{r^2}{2R^2}}.$$

N Wave (profile of ballistic shock wave). An acoustic wave form characteristic of ballistic shock waves consisting of an abrupt rise in pressure (the H discontinuity) followed by a linear pressure decline to a negative relative pressure and an abrupt return (the T discontinuity) to atmospheric pressure.

ODG. Optical deflection unit.

Parasitic (radio antenna). A supplementary antenna in which induced oscillations generate in conjunction with the main antenna a radiation pattern having desired directional sensitivity.

Patterns (target). Lines of iso-sum response and also of iso-response of the directionality-indicating signal (in the receiver) plotted to scale on the target plane so as to indicate the response zones and response lobes obtainable with the FEI.

PCT. Powder-coated tape.

Period (of N-shaped shock-wave profile). Period of time measured from the instant of transit of the head discontinuity H to the instant of transit of the tail discontinuity T past a point fixed in space relative to the air mass.

PU. Power unit.

Pulse Lengthening. An electronic method of increasing the duration of a brief transient electric pulse. A condenser of capacity C provided with a definite high-resistance shunt of resistance R (leak) is charged by a rectifying electronic element. The condenser thereafter discharges slowly with time constant RC starting with the peak value of the charging pulse and decaying exponentially.

Quartz Piezoelectric Microphone. The microphone of this type used for the study of wave forms of shock waves consisted of a pair of quartz plates tightly enclosed in a metal box so that changes (both negative or positive) in the relative external air pressure placed the plates under tension or compression. The resulting piezoelectric charges appearing on the metallized surfaces of the quartz plates were used, through suitable impedance transformers and amplifiers, to furnish on a single-sweep cathode-ray oscilloscope a record of the wave form which was photographically recorded.

Radon. Radium emanation (atomic number 86).

RBC. Resetting binary counter.

Resonant FEI. An earlier form of FEI operating on one radio carrier frequency. Two separate channels of information were established between the FEI transmitter and receiver by the use of two microphones whose disphragms had different and highly sustained natural frequencies of vibration.

Response Patterns. *See* Patterns.

RH. Ring head.

Round-to-Round Reproducibility. The variability of shock-wave amplitude received on different rounds under identical conditions as to caliber, miss distance, range from gun, and receiving apparatus. This variability is attributed to local atmospheric fluctuations of temperature, wind, velocity, turbulence, etc. It is also in part a result of variations in bullet velocity though this effect is small.

Scoring (function of the FEI). The rating of gunners as to excellence of markmanship on the basis of *statistics* regarding the per cent or fraction of all rounds of a given series which fall within specified FEI target zones. Scoring aims to *classify* gunners.

Shock-Wave Discontinuities, *H* and *T*. *See* N Wave.

Static Firing Test. Acoustic test of the response characteristics of FEI transmitters made with the transmitter supported in a fixed position about 35 ft above the ground. Bullets of various calibers are shot at observed miss distances and positions in the target plane. The resulting response of the FEI transmitter is recorded with an FEI field measuring receiving station, or firing error oscilloscope.

Stibitz (Dual) Photographic Theodolite. A method of photographing an aerial target and the tracer bullets fired at it, in which two theodolite motion picture cameras are used separated by a known base line, usually vertical. The method permits of determining the miss distance *when* the bullet has reached the target plane.

Subcarrier System. A method of telemetering in the radio frequency range between 1 and 50 kc.

Sum Response. The sum of the shock-wave signal amplitude from the two microphones in the FEI transmitter.

Tank Circuit. The frequency-determining circuit of an oscillator consisting essentially of a capacity and an inductance in which oscillations occur at substantially the natural resonant frequency.

Target Plane. A plane passing through the FEI transmitter perpendicular to the trajectories of bullets close thereto. Since the miss distances are small relative to the range from the gun, all bullet trajectories are nearly perpendicular to the target plane.

Telemetering. The art, or practice, of transmitting signals (by radio or otherwise) indicative of quantitative measured values of one or more physical variables.

Thermistor. Contraction of the words "thermal resistor" to describe a new type of circuit element whose resistance varies markedly with temperature.

Unit-to-Unit Reproducibility. A measure of the reproducibility of successive FEI transmitter units as to their frequency shift in response to standard excitation of the microphone diaphragms.

Vertical Filter. A filter which has a cutoff characteristic which goes from zero to infinite attentuation within an infinitesimal frequency change.

VSI. An HPI based on velocity of sound in the helium-air mixture.

Zones (sum response). Annular zones in the target plane lying essentially between circles concentric about the transmitter. A shot placed inside a given such zone is so indicated at the receiver either on a tape recorder, a zone counter, or by informing lights. Within limits the radial boundaries of zones can be fixed by adjusting threshold bias potentials in the FEI receiver.

Notation Frequently Used

- f_m — Frequency of the *m*th subcarrier.
- n — Number of channels.
- Δf — Pass-band of each channel of frequency selector. It is assumed that the pass-bands for all n channels are the same.
- F — Sampling rate of commutation system.
- f — Frequency being sampled by commutator.
- F_a — Maximum possible audio frequency in output of frequency-modulated radio link.
- F_c — Maximum audio frequency required from radio link for commutation system.
- F_s — Maximum audio frequency required from link for subcarrier system.
- $\frac{1}{\alpha}$ — Fraction of allotted time each commutator channel is on.

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9. *Progress Report No. 8, Communication Research Involving Impulse Counters. Work accomplished under Contract No. OEMsr-274*, Joseph R. Desch, D3 233, NCR, May 15, 1942. Div. 17-436.2-M3
10. *One Megacycle Impulse Counter and Controlled Impulse Generator*, NCR, July 14, 1942.
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University of Chicago
NDCrc-68 (14, 15); OEMsr-125 (16, 17)

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Massachusetts Institute of Technology—NDCrc-146

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Chapter 10

Johns Hopkins University—OEMsr-1241

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   1b. *Ibid.*, p. 15.
   1c. *Ibid.*, pp. 23, 25.
   1d. *Ibid.*, p. 14.
   1e. *Ibid.*, p. 10.
   1f. *Ibid.*, p. 5.
   1g. *Ibid.*, p. 16.
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3. *Development of Methods for Determining the Proper Seating of Gilding Metal Rotating Bands on 105 MM. Shells in Production (Final Report)*, W. B. Kouwenhoven, OSRD 4869, Johns Hopkins, Mar. 31, 1945, p. 7. Div. 17-610-M2
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   3b. *Ibid.*, Section II, p. 16.
   3c. *Ibid.*, Section III, p. 20.

Chapter 11

University of Pennsylvania—NDCrc-189

1. *Report on Helium Project*, Gaylord P. Harnwell, D3 77, U. Penn, July 2, 1941. Div. 17-323.83-M1
2. *Report on Helium Project*, Gaylord P. Harnwell, D3 113, U. Penn, Sept. 10, 1941. Div. 17-323.83-M1

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Gulf Research and Development Company—OEMsr-266

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Chapter 12

Western Electric Company—OEMsr-868

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Chapter 13

Western Electric Company—OEMsr-498

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2. *The Character of Sounds from Army Vehicles*, F. K. Harvey, G. F. Hull, Jr., R. T. Jenkins, and others, OSRD 4254, Service Project SC-27, WEC, Aug. 21, 1944. Div. 17-421-M1
3. *The Analysis of Sounds from Mortars*, F. K. Harvey, G. F. Hull, Jr., R. T. Jenkins, and others, OSRD 4393, Service Project SC-27, WEC, Nov. 15, 1944. Div. 17-422-M2
4. *Volume I—Analysis of Sounds from Field Artillery and Machine Guns; Volume II—Atlas of Oscillograms of Sounds from Field Artillery and Machine Guns*, G. F. Hull, Jr., R. T. Jenkins, J. B. Kelly and N. G. Wade, OSRD 4594, Service Project SC-27, WEC, Jan. 15, 1945. Div. 17-422-M3

Chapter 14

Carnegie Institute of Technology—NDCrc-84

1. *Thermistor Investigation Report No. 1*, J. F. Lamb and B. R. Teare, Jr., D3 23, Carnegie Tech, Apr. 8, 1941.
2. *Self-Balancing and Phase Shifting Bridge Circuits*, J. F. Lamb and B. R. Teare, Jr., D3 51, Carnegie Tech, June 1, 1941.

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3. *Trigger Amplifiers*, T. H. Johnson, D3 6, Franklin Institute, Feb. 28, 1941.
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10. *Investigation of Telemetric Flow Meter for Automotive Fuels*, E. M. Palmer, D3 255, Gulf Research, June 30, 1942.
11. *Development of Electric Frequency Meter, or Tachometer*, L. L. Nettleton, D3 264, Gulf Research, Aug. 10, 1942. Div. 17-323.82-M1

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12. *High Speed Thermistors*, Roger W. Hickman, D3 22, Harvard, Apr. 5, 1941.
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16. *Thermistor Investigations*, Roger W. Hickman, D3 158, Harvard, Dec. 29, 1941. Div. 17-451-M7
17. *Thermistor Investigations*, Roger W. Hickman, D3 194, Harvard, Feb. 15, 1942. Div. 17-451-M7
18. *Thermistor Investigations*, D3 242, Harvard, June 6, 1942. Div. 17-451-M7
19. *Thermistor Investigations (Final Progress Report)*, D3 272, Harvard, Aug. 7, 1942. Div. 17-451-M8

Massachusetts Institute of Technology
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20. *Properties of Thermistor Materials*, A. B. White and W. B. Nottingham, D3 37, MIT, May 1, 1941.
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22. *Progress Report Contract No. OEMsr-155*, A. V. deForest, D3 151, MIT, Dec. 13, 1941.
23. *Progress Report Contract No. OEMsr-155*, A. V. deForest, D3 175, MIT, Jan. 31, 1942.
24. *Firing Strains in a 37-mm Field Gun*, A. V. deForest, D3 183, MIT, Feb. 16, 1942. Div. 17-453-M1
25. *Report on Contract No. OEMsr-155*, A. V. deForest, D3 204, MIT, Apr. 3, 1942.
26. *Final Progress Report on Contract No. OEMsr-155*, A. V. deForest, D3 287, MIT, Aug. 31, 1942.
27. *High-Speed Strain Transient Recording and Measurement Internal Gun Diameter under High Hydrostatic Pressure*, A. V. deForest, A. C. Ruge, and G. S. Burr, D3 339, MIT, Dec. 1, 1942.
28. *Progress Report Project No. NDCrc-179*, R. D. Evans, D3 63, MIT, June 15, 1941.
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30. *Development of an Instrument Capable of Measuring the Radon Content of Breath and Room Air Samples*, R. D. Evans, S. C. Brown, and L. G. Elliott, D3 136, MIT, Oct. 31, 1941.

Northwestern University—NDCrc-62

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32. *The Thermistor Bolometer*, Noel C. Jamison, D3 80, Northwestern, July 9, 1941. Div. 17-451-M5

Rensselaer Polytechnic Institute—NDCrc-54

33. *Progress Report on Thermistor Investigation*, D3 26, RPI, Apr. 15, 1941. Div. 17-451-M3
34. *Report on Thermistor Investigation*, D3 85, RPI, July 31, 1941. Div. 17-451-M3

University of Pennsylvania
NDCrc-102 (35-37); OEMsr-110 (38-41)

35. *Report No. 1 on Strain Gauge Investigation*, Gaylord P. Harnwell, D3 32, U. Penn, Apr. 25, 1941. Div. 17-436.511-M1
36. *Report No. 2 on Strain Gauge Investigation*, Gaylord P. Harnwell, D3 59, U. Penn, June 10, 1941. Div. 17-436.511-M1
37. *Final Report on Strain Gauge Investigation*, Gaylord P. Harnwell, D3 94, U. Penn, Aug. 10, 1941. Div. 17-436.511-M2
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39. *Report on Strain Gauge Investigation*, Gaylord P. Harnwell, D3 174, U. Penn, Jan. 15, 1942.
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41. *Development of Resistance Wire Strain Gauges* (*Final Report*), Gaylord P. Harnwell, D3 284, U. Penn, September 1942.

University of Minnesota
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42. *Progress Report Covering Thermistor Investigations*, D3 18, U. Minnesota, Apr. 1, 1941.
43. *Final Report Covering Thermistor Investigations*, Otto H. Schmitt, D3 52, U. Minnesota, June 1, 1941. Div. 17-451-M1
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45. *Final Report on Thermistor Investigation*, Otto H. Schmitt, D3 177, U. Minnesota, Feb. 1, 1942. Div. 17-451-M1

Yale University—NDCrc-107

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47. *Report Number Two—Contract NDCrc-107*, [Fundamental Properties of Thermistors, and Their Applicability to Filters], Carol G. Montgomery, D3 53, Yale, June 1, 1941. Div. 17-451-M2
48. *Final Report—Contract NDCrc-107*, Carol G. Montgomery, D3 86, Yale, July 31, 1941.

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The contract information given below is for Division 17 work reported in (or related to) this volume. Contract information associated with Division 17 work reported in other volumes of the Division 17 Summary Technical Report is given in those volumes.

The work under contracts whose numbers are marked with an asterisk (*) is not discussed anywhere in the Division 17 STR. For details of such work the reader is referred to the NDRC Bi-Monthly Summaries. The contracts themselves are listed here for completeness of contract information.

Contract Number	*Name and Address of Contractor*	*Subject*
NDCrc-22*	Polytechnic Institute of Brooklyn New York, New York	Preparation of pure amino guanidine sulphate.
NDCrc-54	Rensselaer Polytechnic Institute Troy, New York	Studies and experimental investigations in connection with the application of thermistors to electrical circuits of particular types.
NDCrc-55	Franklin Institute of the State of Pennsylvania Swarthmore, Pennsylvania	Studies and experimental investigations in connection with the application of thermistors to electrical circuits of particular types.
NDCrc-60	Regents of the University of Minnesota Minneapolis, Minnesota	Studies and experimental investigations in connection with the application of thermistors to electrical circuits of particular types.
NDCrc-62	Northwestern University Evanston, Illinois	Studies and experimental investigations in connection with the application of thermistors to electrical circuits of particular types.
NDCrc-63	National Cash Register Company Dayton, Ohio	Studies and experimental investigations in connection with counter tubes.
NDCrc-68	University of Chicago Chicago, Illinois	Studies and experimental investigations in connection with counter tubes.
NDCrc-84	Carnegie Institute of Technology Pittsburgh, Pennsylvania	Studies and experimental investigations in connection with the application of thermistors to electrical circuits of particular types.
NDCrc-102	University of Pennsylvania Philadelphia, Pennsylvania	Studies and experimental investigations in connection with the present state of the use of strain gauges and their associated equipment in the testing of military vehicles with a comparison of existing methods, and a recommendation as to what is needed for the development of satisfactory telemetric strain gauges.
NDCrc-140	Western Electric Company, Inc. New York, New York	Studies and experimental investigations in connection with thermistor circuits.
NDCrc-142	Massachusetts Institute of Technology Cambridge, Massachusetts	Studies and experimental investigations in connection with the application of thermistors to electrical circuits of particular types.
NDCrc-146	Massachusetts Institute of Technology Cambridge, Massachusetts	Studies and experimental investigations in connection with counter tubes and circuits, to develop high-speed counter tube circuits in decade rings, covering the use of thyratrons, pentodes and double triodes, and the development of a "digitron" tube and counter circuit using this tube.

Contract Number	*Name and Address of Contractor*	*Subject*
NDCrc-179	Massachusetts Institute of Technology Cambridge, Massachusetts	To conduct an investigation on the development of an instrument capable of measuring the radon content of breath and room air samples.
NDCrc-189	The Trustees of the University of Pennsylvania Philadelphia, Pennsylvania	To conduct an investigation on the development of a compact, portable and telemetering helium purity indicator.
NDCrc-194	Hazeltine Electronics Corporation New York, New York	Studies and experimental investigations in connection with telemetering readings, and, more particularly, (i) conduct an investigation on the development of radio methods of telemetering readings of dials of airplane instruments necessary for blind flying, (ii) furnish, transportation paid, where and as directed by the Contracting Officer or an authorized representative, a working model of at least one instrument capable of telemetering the airplane instrument dial readings, (iii) make modifications of the above described instrument as specified by the Contracting Officer or an authorized representative, (iv) conduct further studies and experimental investigations of the above subject as requested from time to time by the Contracting Officer, with particular reference to the requirements of various military and naval applications of the device, (v) deliver models of the modified instrument as requested by the Contracting Officer or an authorized representative from time to time, and (vi) conduct flight tests of the described instrument as directed by the Contracting Officer or an authorized representative.
OEMsr-110	University of Pennsylvania Philadelphia, Pennsylvania	Studies and experimental investigations in connection with the development of strain gauges.
OEMsr-125	University of Chicago Chicago, Illinois	Studies and experimental investigations in connection with an electronic ratchet tube for use as a high-speed counter.
OEMsr-155	Massachusetts Institute of Technology Cambridge, Massachusetts	To study and investigate experimentally the application of strain gauges to the measurement of the expansion of gun barrels under hydrostatic pressure up to one hundred fifty thousand pounds (150,000 lb) per square inch, and to develop equipment for measurement of firing strains in field guns.
OEMsr-241	The Board of Trustees of the University of Illinois Urbana, Illinois	Studies and experimental investigations in connection with (i) the evaluation of the use of 3 to 20 million volt x-rays for the radiography of thick metal sections, (ii) the construction of one (1) Kerst Electron Accelerator, together with accessory equipment, (iii) the simplification of design of 4.5 million volt unit, and applications thereof, and (iv) the development and fabrication of ceramic bodies and glazes suitable for vacuum acceleration chambers for use with the 4.5 million volt and 20 million volt betatrons.
OEMsr-247	Rudolph Wurlitzer Company North Tonawanda, New York	Studies and experimental investigations in connection with a special method of telemetering strain indications from an aircraft in flight, with means also available for the telemetering of aircraft instruments, in accordance with tentative specifications outlined by Section 17.2 of the National Defense Research Committee.

Contract Number	*Name and Address of Contractor*	*Subject*
OEMsr-254	The Brush Development Company Cleveland, Ohio	Studies and experimental investigations in connection with the development of (i) a transient strain analyzer involving a three-element oscillograph capable of recording high rates of deformation in metals and of explosion pressures under water, (ii) an improved magnetic recording medium, and (iii) means for improvement of the recording mechanism with particular reference to the recording head.
OEMsr-266	Gulf Research and Development Company Pittsburgh, Pennsylvania	Studies and experimental investigations in connection with the development of (i) improved methods of submarine mine control, (ii) a security device, (iii) an improved helium purity indicator for use in range-finders and lighter-than-air craft, (iv) a device for the determination of the quantity of fuel in the tanks of aircraft, (v) an indicator mine and associated devices and methods for determining the effectiveness of various explosive means of clearing minefields, and (vi) other instruments and devices of warfare when and as requested in writing by the Contracting Officer or an authorized representative.
OEMsr-274	The National Cash Register Company Dayton, Ohio	Studies and experimental investigations in connection with (i) the development of improved electronic tubes and circuits for use in high-speed counting devices, (ii) the development of a new system of secret communication involving electronic counters, and (iii) the development of electronic and mechanical equipment.
OEMsr-275	The National Cash Register Company Dayton, Ohio	Studies and experimental investigations looking toward the design and construction of special high-speed electric counter and recording units.
OEMsr-278*	Purdue Research Foundation Lafayette, Indiana	To conduct studies and experimental investigation in connection with the development of improved radio control equipment for target airplanes, to perform preliminary tests of such equipment in a target airplane, and to furnish examples of the apparatus developed hereunder.
OEMsr-294	Massachusetts Institute of Technology Cambridge, Massachusetts	(i) Design an x-ray generator capable of operating continuously at voltages up to two (2) million volts, under field conditions, with a high degree of reliability, (ii) construct five (5) such electrostatic x-ray generators, capable of operating at voltages up to two (2) million volts or higher, (iii) train Navy personnel in the operation of such equipment, (iv) assist in installation of four (4) machines being supplied to the Navy Department, Bureau of Ordnance, and (v) standardize design of all machines and supply stock of spare parts adaptable to all machines as a result of this standardization.
OEMsr-314	RCA Manufacturing Company, Incorporated Camden, New Jersey	Studies and experimental investigations in connection with the development of a method of telemetering aircraft instruments by means of television, including the development of a suitable television transmitter and receiver.

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Contract Number	*Name and Address of Contractor*	*Subject*
OEMsr-383*	Swarthmore College Swarthmore, Pennsylvania	Studies and experimental investigations in connection with the development of a simple and cheap sound locator device for locating aircraft by civilian defense spotters.
OEMsr-498	Western Electric Company New York, New York	Studies and experimental investigations in connection with (i) obtaining an acoustical analysis of sounds from machine guns and from field pieces of larger caliber and (ii) obtaining an acoustical analysis of the sound from projectiles from these guns and of battle noises and other sounds of combat significance.
OEMsr-600	California Institute of Technology Pasadena, California	Studies and experimental investigations in connection with the development of (i) a scoring system which would give direct indication of the magnitude and direction of firing errors in shooting anti-aircraft projectiles at a small towed glider, (ii) an acoustic device for the scoring of rockets fired from an airplane at a surface or airborne target, and (iii) an acoustic firing error indicator adapted for use with towed targets of several types used in anti-aircraft gunnery training and calibrated for several calibers of fire; and the adaptation of the device to the scoring of rockets fired from planes at both aerial and surface targets.
OEMsr-680*	Massachusetts Institute of Technology Cambridge, Massachusetts	Studies and experimental investigations in connection with the development of ferro-electric salts whose curie temperatures occur at or near room temperature for use in microphones of increased sensitivity.
OEMsr-823	Hathaway Instrument Company Denver, Colorado	Studies and experimental investigations in connection with the development of multielement oscillograph and associated equipment according to specifications laid down by the Aberdeen Proving Ground, Aberdeen, Maryland.
OEMsr-868	Western Electric Company New York, New York	(i) Studies and experimental investigations in connection with the development of a system including sound effects, records and loud speakers for reproduction of battle noises, and the furnishing of sound sequences simulating naval battles, and (ii) the instruction and training of Naval personnel in the operation and maintenance of the equipment developed.
OEMsr-920	Purdue Research Foundation, Purdue University Lafayette, Indiana	Studies and experimental investigations in connection with the development and construction of improved three-element cathode ray oscillograph, including three signal channel units and one timing unit.
OEMsr-1037	Princeton University Princeton, New Jersey	Studies and experimental investigations in connection with the (i) development of electronic commutation telemetering transmitting and receiving units with associated amplifiers, input circuits, output circuits, and radio link, (ii) construction of one complete 18-channel commutation telemetering system and flight test of this system, (iii) construction of two additional complete telemetering systems of at least eighteen (18) channels each, to serve as field test and manufacturing prototypes, (iv) development of a

Contract Number	*Name and Address of Contractor*	*Subject*
OEMsr-1037 (*Continued*)		cathode ray recording system to allow recording of the received commutation signal with simplified apparatus adaptable to the Armstrong system of frequency modulated radio link, (v) development of an improved electronic commutation system accommodating approximately thirty (30) items of intelligence, utilizing rotary beam scanning tubes for switching in place of present circuits, (vi) development of methods of subcommutation for the transmission of additional items of intelligence in conjunction with the present system and the proposed new system, (vii) development and adaptation of a method of pulse modulation radio transmission to the transmission of signals derived from the rotary beam commutator, and (viii) development of telemetering system for LARK in accord with general specifications outlined in letter from Chief, BuAer to Chief, Research and Inventions, Navy Department, dated 19 July 1945, reference C21302, and construction, preliminary test, and delivery of one model of said system, including two complete ground receiving stations mounted in trucks to be provided by the Navy Department.
OEMsr-1099	C. G. Conn, Ltd. Elkhart, Indiana	Studies and experimental investigations in connection with the development of fourteen (14) channel strain gauge telemetering equipment, incorporating wattmeter circuits previously developed.
OEMsr-1108	Mission Bell Radio Manufacturing Company, Incorporated (later Hoffman Radio Manufacturing Company) Los Angeles, California	Studies and experimental investigations in connection with the construction of thirty two (32) complete directional receivers for the firing error indicator and two thousand two hundred (2200) directional transmitters.
OEMsr-1153	Allis-Chalmers Manufacturing Company Milwaukee, Wisconsin	Fabricate, assemble and deliver to the Government . . . Betatron equipment . . . manufactured in strict accordance with the written specifications and instructions heretofore furnished to the vendor.
OEMsr-1203	Faximile, Incorporated New York, New York	Studies and experimental investigations in connection with (i) the development, construction and testing of at least three (3) models of a device for indicating and recording the deflection time curve of a bulkhead or similar structure under the force of an explosion, and incorporate therein certain desirable bridge circuits which field tests have shown to be desirable, (ii) the development, construction, and testing of at least one model of a device for indicating and recording the deflection time curve of a small scale model of a bulkhead of similar structure under the force of an explosion, and (iii) the extension of operating range of the device already developed under the subject contract in order to make it operable on deflections of the order of three (3) feet. Delivery of models and devices constructed hereunder together with six (6) exciter coils and three (3) spare receiving coils, detailed drawings, specifications, reports and directions for operation.

Contract Number	*Name and Address of Contractor*	*Subject*
OEMsr-1211	White Research Associates Boston, Massachusetts	Studies and experimental investigations in connection with the (i) development and construction of four channel oscillograph equipment, including wide band direct coupled amplifiers, timing apparatus, and sweep circuits in accordance with preliminary specifications submitted by the Aberdeen Proving Ground; (ii) design and construction of high speed camera and developing apparatus to be used in connection with (i); (iii) installation of the equipment developed and constructed under (i) and (ii) hereof, in a trailer to be supplied by the Army Ordnance Department, as directed by the Scientific Officer and officials of the Aberdeen Proving Ground; and (iv) development and construction of one additional trailer-mounted oscillograph unit in accordance with Naval Proving Ground specifications, and one dolly-mounted oscillograph unit for laboratory use.
OEMsr-1241	Johns Hopkins University Baltimore, Maryland	Studies and experimental investigations in connection with (i) the development of non-destructive test apparatus for determining the seating of rotating bands on projectiles, with emphasis on apparatus which is simple, rugged, and rapid, to allow application to production testing, and (ii) associated methods for the determination of variations in sheet wall thickness.
OEMsr-1308	Shell Oil Company, Incorporated Houston, Texas	Studies and experimental investigations in connection with the design and construction of a mobile timing laboratory.
OEMsr-1369	The Texas Company New York, New York	Studies and experimental investigations in connection with the design and construction of one or more devices for the measurement of wall thickness of aircraft propeller blades, based upon the absorption, or other characteristics, of gamma radiation, or other suitable radiation.
OEMsr-1399	Raymond Rosen and Company Philadelphia, Pennsylvania	Manufacture of (in accordance with specifications and instructions) and delivery of two complete 18 channel electronic strain gauge telemetering systems, including specified equipment.
OEMsr-1457	Western Electric Company, Incorporated New York, New York	Studies and experimental investigations in connection with the development for manufacture of a condenser microphone suitable for use in acoustic firing error indicator.

The projects listed below were transmitted to the Executive Secretary, NDRC, from the War or Navy Department through either the War Department Liaison Officer for NDRC or the Office of Research and Inventions (formerly the Coordinator of Research and Development), Navy Department.

Service Project Number	*Subject*
	Army Projects
AC-20	Electric strain gauge suitable for remote indicating and recording.
AC-34	Development of a thermistor and associated control circuits for use in heat responsive target seeking, controllable bombs.
AC-40	Development of telemetering equipment (later AC-224.02).
AC-41*	Radio control of model aircraft.
AC-46	Firing error indicator.
AC-67	Design and development of apparatus for the air forces mobile instrument trailer.
AC-79	The development of some method or device for measuring the wall thickness of a hollow steel propeller blade.
AC-224.02	Research and development work on radio telemetering of strain gauge indications on aircraft (formerly AC-40).
AC-238.02	Research on magnetic recording materials (formerly SC-111).
OD-73	Multi-element oscillograph.
OD-80*	Camera clock for range bombing instrumentation.
OD-90	Development of bomb instruments.
OD-102	Cathode-ray oscilloscope equipment.
OD-124	Studies of seismograph detectors for determining the time of impact of bombs.
OD-140	Mobile oscillograph.
OD-148	X-ray radiography—betatron.
OD-151	Methods of determining the seating of rotating bands on projectiles.
SC-27	Investigations of sound spectrum of ordnance equipment.
SC-111	Research on magnetic recording material (later 238.02).
SC-134	Rocket telemetering.
	Navy Projects
NA-133	Telemetering.
NA-134	Telemetering.
NA-152	Telemetering (14 or more channels indicating rapidly varying strain gauge resistances).
NO-123	Design, fabrication and installation of three two-million volt x-ray machines for mine or bomb recovery work.
NO-123 Ext.	Design, research and development of sealed-off x-ray tube.
NO-173	Firing error indicator.
NO-260	Scoring of air to air rocket firing.
NS-197	Development of deflection-time measuring devices.

*This project was assigned to Divisions 5 and 17.

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